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SHUTTLE ATTACHED MANIPULATOR SYSTEM

SIMULATION 2 - SATELLITE SERVICING

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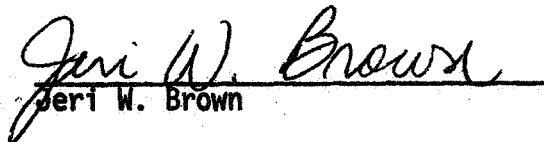
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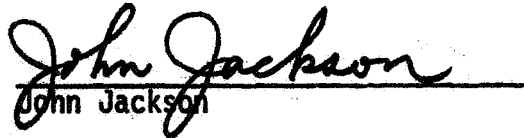
SHUTTLE ATTACHED MANIPULATOR SYSTEM

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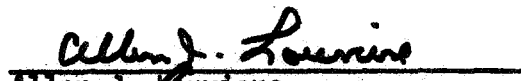
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SUMMARY

Satellite servicing by replacement of modular subsystem assemblies was simulated using the CAM 1400 Manipulator Simulation Facility at JSC with prototype hardware furnished by GSFC. All test subjects were able to perform the entire task, although some operations were more difficult than should be considered for normal flight operations.

INTRODUCTION

The Space Shuttle will utilize a manipulator to perform payload handling functions. In order to develop the technology necessary for the design of a Shuttle Attached Manipulator System (SAMS), a modified commercial manipulator is being used to obtain data on Shuttle-related tasks.

This report describes the simulation of replacement of modular subsystem packages as a means of servicing orbiting satellites. This simulation is the second in a series of tests designed to investigate various problems associated with SAMS development.

OBJECTIVES

The principal objective of this simulation was to verify the feasibility of installing and removing modular components of an orbiting spacecraft by manipulator. Corollary objectives were to:

1. Evaluate the suitability of terminal devices and grappling fixtures used.
2. Determine the feasibility of eccentrically located grappling points.
3. Determine the feasibility of using a second manipulator to hold the spacecraft being serviced.
4. Define TV system requirements.
5. Establish the ability of manipulator to secure and release latches against required preload.
6. Verify operation of an automatic umbilical connector.
7. Identify problem areas and recommend solutions.

TEST SET-UP

General

The simulation was carried out with the CAM 1400 manipulator and air-pad floor at JSC. This facility is described in detail in reference 1.

The hardware consisted of a subsystem module engineering test article ("module") and mating female check fixture ("spacecraft") built by the Goddard Space Flight Center as part of the Large Space Telescope program. Figure 1 illustrates the salient features of these items. The module as used for the simulations weighed 280 pounds.

In operation, the module slides into the opening in the spacecraft on four rails, one at each corner. Maximum lateral or vertical misalignment for initial insertion was 0.25 inch at each corner, including misalignment in roll. After achieving initial insertion, the rails had 0.04 inch clearance for the 18 inches of motion until the module was seated. This clearance was sufficiently close to cause binding with pitch or yaw misalignments of one or two degrees.

Equipment Mounting

The general arrangement of the test set-up is illustrated in Figure 2. The module was suspended from a cantilever beam attached to a freebody on air pads. The suspension system (Figure 3) was arranged to facilitate adjustment of the single point of suspension to coincide with the center of gravity of the module, so that the module could rotate freely about three axes. The air pads permitted essentially frictionless motion in a horizontal plane. Vertical motion was achieved during the first runs by manually regulating the air pressure in a cylinder in the freebody. However, this proved unsatisfactory and most runs were made with the freebody and attached beam locked at the correct height. Thus the module could move in five degrees of freedom.

The "spacecraft" was mounted on an air-pad base, although the air pads were inflated for only one test configuration (see Test Configurations section). The center of the spacecraft was 21 feet from the operator's station.

The tool used to lock and release the rotary pins was stowed on the floor at a marked location when not in use (Figure 2). The tool used for the push-type pins would not stand alone and was stowed in a receptacle at the same location.

Television

In addition to the operator's direct view of the task, six TV cameras were located as shown in Figure 2. Camera 1 was mounted on top of the boom about three feet beyond the elbow. Cameras 2 and 4 were positioned about four feet above the floor to view the left and right sides, respectively, of the spacecraft. Camera 3, also about four feet off the floor, was located to provide a line of sight in the plane of the front face of the spacecraft. Camera 5 was mounted on the manipulator power supply about nine feet above the floor and was set for an overall view of the entire spacecraft. Camera 6 was mounted to view the operator's face and hands and a clock directly behind the operator; this was the only view not available to the operator. Cameras 1, 2, 3 and 4 were controllable by the operator in pan, tilt, zoom and focus.

Two monitors were located, one above the other, directly in front of the operator. The lower monitor displayed cameras 2 and 4 at all times on a split screen. The upper monitor displayed any camera (except number 6) selected by the operator. Brightness and contrast of each monitor were adjustable by the operator. The pan-tilt-zoom-focus controls, within reach of the operator's left hand, were automatically connected to the camera (except number 5) selected on the upper monitor. For uniformity, camera 1 was selected and set for a closeup view of the end effector prior to each run and cameras 2 and 4 were set for medium close ups of the upper left and upper right corners of the spacecraft. Once started, the operator was given complete freedom of choice.

A video tape recorder was used to record each run. The view on the upper monitor was recorded, with camera 6 (the operator's face and hands) inserted in one corner of the picture by means of a screen splitter. In this way, a record was made of: the progress of the task (including timing); which camera the operator was using; the time spent watching the upper monitor, lower monitor, camera controls or the task itself; and the operator's hand movements.

A floodlight was placed in front of the power supply and six feet off the floor to enhance the ambient illumination. For one test (see following section), the light was placed behind camera 5 and about eleven feet off the floor.

For runs using TV only, a Fomecor screen was used to block the operator's view of the module and spacecraft.

Test Configurations

Six different configurations were used for this simulation to evaluate a number of questions relating to the satellite servicing problem. These configurations are summarized in Table 1, with the distinguishing feature of each emphasized for convenience.

Configuration A differed from the others in that the four corner pins were locked and released by rotating the head of a screw attached to the pin. A special wrench was fabricated by GSFC to interface between the screw heads and the end effector jaws. This method was intended to permit the manipulator, which has a limited tip force capability, to overcome the large pre-load required by the module design. However, the low rotation speed of the end effector made the task monotonous and fatiguing (locking or releasing each pin required about a minute after the wrench was placed in position).

To alleviate this problem, the pins were converted to the original concentric push-pin arrangement (configuration B) by installing lighter pre-load springs. In this design, the outer portion of the actuator is pushed to extend the pin and the center portion to release the locking balls (Figure 4). Thus, pins were locked by depressing both parts simultaneously, then sliding the tool off vertically so that the center portion was released first. The pins were released by touching only the center portion, thus releasing the locking balls and allowing the spring to retract the pin. These pins were used for all subsequent runs, so that configuration B should be considered the baseline, even though more runs were recorded with configuration A.

Configuration C eliminated direct vision so that the TV monitors provided the only visual cues. It was otherwise identical to B, and was intended to evaluate the performance degradation, if any, resulting from loss of a direct ("out-the-window") view.

Configuration D used a single light source, a floodlight behind and about two feet above camera 5, in an attempt to simulate unidirectional illumination such as sunlight. However, even with all other lights in the test area turned off, sufficient ambient and reflected light existed to fill the shadows sufficiently for visual detection. Consequently, these runs were made with TV only, because the camera sensitivity could be adjusted to eliminate all visibility in the shadows.

Configuration E differed from B in that the grappling fixture was moved from its center position to a point 18 inches from the right end of the module and 4 inches from the upper edge. The purpose of this was to evaluate the problems associated with close-tolerance guide rails where the module center of gravity is not aligned with the grappling fixture.

Configuration F was the same as B except that the spacecraft was floated on air pads and tethered with 3/8 inch nylon rope to the manipulator base and to a column behind the spacecraft (see Figure 2). The objective of this test was to simulate a spacecraft held by a flexible manipulator arm during servicing.

As may be seen in Table 1, most of the runs were made with configurations A, B and C. Time constraints imposed by the GSFC test schedule made extensive runs with the last three configurations impractical. However, since the few runs that were made appeared to demonstrate feasibility, no effort was made to expand the data with additional operators.

PROCEDURE

Test Sequence

A detailed test procedure was prepared and is reproduced as Appendix A.

Each complete "run" consisted of installing and removing the module once, and included the following steps:

1. Grapple module
2. Align module and insert in spacecraft
3. Release module and pick up pin locking tool
4. Lock all four pins
5. Stow tool
(Break)
6. Pick up tool
7. Release all four pins
8. Stow tool
9. Grapple module
10. Remove module from spacecraft
11. Release module

The test subject was allowed a few minutes for warm-up prior to beginning the run as well as a break, during which the manipulator was shut down, at the mid-point of the run. Neither the warm-up nor the break was mandatory and some subjects preferred to continue without stopping, although fatigue became evident in other subjects after about half an hour.

Before each subject's first run, he was given printed instructions (included in this report as Appendix B) and allowed to examine the test equipment and ask any questions he desired. The TV camera locations and controls were also explained. The printed instructions were made available for subsequent runs, and additional questions for clarification were permitted at any time.

Data

Two primary data sources were used. One was the video tape recording discussed in the Television section. The other was a record of elapsed

time for each major event as listed in the test sequence above, including notations of anomalous events such as dropping the pin locking tool. Where these anomalies were caused by equipment problems, the time lost was deducted from the subject's total time. If operator error was the cause, no deduction was made, even though the operation had to be halted while a dropped tool was placed so that it could be picked up again, or a module tilted and jammed in the rails was freed by hand.

A crew of two was used for most of the runs: a test director to supervise the test, record event times and record and correct anomalies, and a TV technician to operate the video tape recorder and other TV equipment. During the first runs, a third man operated the air pressure regulator to control the height of the module.

Test Subjects

Eighteen test subjects took part in this simulation. These subjects were all JSC engineers involved in various aspects of the Shuttle program and included two astronauts. At the beginning of the tests, four of these had no prior experience with the CAM 1400, four had less than one hour, six had between one and two hours, and four had between five and eight hours of experience. Additional experience accumulated during the test series varied from two to four hours per man. Ten of the eighteen also took part in Simulation 1 - Grappling a Fixed Object (Reference 2) and four participated in a series of tests evaluating compliance and force feedback (Reference 3). See Table 2 for details. The subject identification used in Reference 2 has been retained for the same individuals for ease of comparison.

In addition to the regular test subjects, a number of persons attempted the task on an impromptu, informal basis. These included personnel from JSC and other NASA centers, contractor representatives and visitors from Germany and the Soviet Union. Except for a few contractor personnel, none had any manipulator experience.

ANALYSIS

General

The runs performed by the test subjects were, without exception, successful, even though total times as high as 83 minutes were recorded. In addition, of 28 informal runs by visitors, 23 were successful, even though most had no prior experience, the task was explained only in general terms, and many of the visitors were middle-aged, had poor eyesight or were otherwise not physically on a par with the test subjects.

One, General Shatalov of the Soviet Union, spoke no English (his attempt, however, was successful). The principal reasons for the few failures were fatigue, loss of interest after a few minutes, and time limitations of the visitors' schedules. It is concluded that, within the limitations of the test set-up, feasibility of the basic task has been established, even for inexperienced, untrained operators.

Task Times - Configurations A, B and C

After the simple success/failure criterion, task times are the most fruitful source of data. These times are compiled for the 87 recorded runs in Appendix C, Tables C-1, C-2, C-3 and C-4, each run being broken down into 16 specific tasks for timing purposes. It is implicitly assumed that performance time for a given task can be used as a rough measure of task difficulty, although this is not always true. Since each task embodied a different set of problems for the operator, they will be considered individually.

Module Grappling

The first task, grappling the module, occurs twice, as task 1 during installation and as task 15 during removal. In both cases the usual learning curve can be seen in the configuration A and B runs, which were identical in this task (see Figure 5). This is also true if the tasks are considered in chronological order, viz., A_1 (1), A_1 (15), A_2 (1), A_2 (15), etc., apparently verifying that the two grapplings are identical (subscripts indicate the first, second and third runs with configuration A by each subject). There were in fact two differences. For task 1, the module was resting against the spacecraft but was free, so that accidental premature contact by the jaws could cause large motions of the module and result in lost time while the end effector was repositioned for the new attitude of the module. This was not the case in task 15, where the module was retained in the spacecraft while grappling took place. On the other hand, the operator had an opportunity to prepare in advance for task 1 (by adjusting cameras, etc.), whereas time for task 15 started as soon as the pin locking tool was stowed. This latter difference is emphasized in configurations C and D (TV only), where task 15 took significantly longer than task 1. Where direct vision was available, the two differences appear to offset each other.

Module Insertion

Task 2, inserting the module into the spacecraft, was the most difficult operation. As may be seen in Figure 6, the distribution of insertion times is scattered in the beginning (as for module grappling) and remains

scattered, although the average time decreases with experience, whereas module grappling time tends to be less scattered in the later runs (cf. Figure 5, configuration B). It is inferred that a successful insertion at any one attempt is almost a matter of chance, an inference that is borne out, at least subjectively, by experience. If this is true, it can also be inferred that this task approaches the limit of acceptable operational reliability, and that nothing more difficult than this should be considered.

A number of problems contributed, some arising from the module design and some from the test set-up. As has been noted, initial insertion required positional accuracy of ± 0.25 inch at each corner, a misalignment that is difficult or impossible to perceive from the operator's station. After insertion, the close-tolerance rails jammed easily with small pitch or yaw errors that were also difficult to detect visually. Some subjects "felt their way in" after initial insertion using the force feedback of the manipulator, stopping at the first slight jam and correcting accordingly. This technique was generally successful. Others would attempt to seat the module as quickly as possible, an approach that sometimes succeeded and sometimes jammed so hard that the module had to be freed by hand.

The module suspension was a source of considerable difficulty. It was in effect a two-mass, spring-connected system, the 280-pound module being one mass and the 1000-pound freebody the other. Air pad friction was so low that there was essentially no damping. The result was that rapid translational inputs to the module toward or away from the freebody generated an oscillatory motion of the two masses that was very difficult to control. The only effective way to avoid the problem was to move the module as slowly as possible while attempting to align it with the spacecraft. Since this suspension system would not exist in flight hardware, it is assumed that, to this extent at least, the simulation presented a more difficult task than actual flight operations.

The fixed vertical position of the module center of gravity created two abnormal conditions. First, vertical translation was neither possible nor necessary; thus the operator's task was somewhat simplified. Second, vertical motion of the end effector caused a rotation in pitch because the vertical force capability of the manipulator, acting several inches from the suspension point, overrode the gripping force (and hence torque capacity) of the end effector. This also had the effect of moving the ends of the rails in the opposite direction from the vertical force input since the suspension point acted as a fixed pivot. The overall effect was extremely abnormal and confusing, although most of the test subjects readily adapted to the situation once they understood it.

Task performance was greatly enhanced by efficient use of television. The optimum appeared to be as follows (see Figure 2 for camera locations):

1. Keeping module centered in front of spacecraft by direct vision, use camera 3 for yaw and pitch alignment.
2. Switch to camera 5, which gave, in addition to an overall view, a line of sight parallel to the upper right pin. This made perception of lateral position errors both easy and accurate. Simultaneously, use cameras 2 and 4, set for identical views of the upper left and right rails, to detect roll errors.
3. After initial insertion, use cameras 2 and 4 to maintain equal travel of both sides during final seating, together with camera 3 for equal travel top and bottom, if any binding or jamming starts to develop.

Each subject had his own method, but most differed from the above in that camera 5 was used little, if at all. This may be because of the inferior image quality of this camera or because there was no pan-tilt-zoom capability.

Many subjects attempted insertion with direct vision only, or with cameras 2 and 4 as the only supplementary views. The module was almost invariably positioned too far to the right in these cases, with the result that the left end of the module missed the rails and passed inside the spacecraft while the right side was stopped by that side of the spacecraft. On many occasions, the module was pushed so far that the grappling fixture was twisted out of the jaws, requiring the operator to regrasple and start over. It is believed that this problem was caused by attempting to align the right-hand rails (the only ones directly visible) with the mating track in the spacecraft without making sufficient allowance for the offset point of view, either direct or camera 4 (see Figure 7).

Even though most cues for module alignment could be better obtained from TV than from direct vision, average performance suffered significantly when the direct view was eliminated (Figure 6, configuration C). However, average performance may be misleading, since six of the thirteen subjects (I, J, L, N, Q and T) who tried configuration C had better times than with direct vision (configuration B). The average time is higher because the subjects who did worse without direct vision did much worse. No satisfactory explanation for this variation has been found. Most, but not all, of the experienced operators did worse without direct vision, suggesting the possibility that experience, largely with direct vision, tends to develop a dependence on direct vision that makes a TV-only situation more difficult. Such a hypothesis, however, must be considered more as speculation than a valid explanation.

As an additional alignment aid on configurations C through F, white tapes were placed on the module and spacecraft so as to provide an apparently continuous line when the module was correctly aligned. They were little used, however, because they gave no better information than was available from the module itself. The value of alignment aids of this type will be greater if the configuration of the payload is such that, alone, it provides insufficient cues.

Tape was beneficial in reducing reflections from the ends of the tracks in the spacecraft. These reflections made visibility of the tracks extremely poor, and alignment was very difficult. Elimination of the reflections made alignment much easier.

An umbilical connector mated automatically when the module was fully seated. Mating was confirmed by battery-powered lights which indicated continuity. The connector functioned perfectly. However, battery drain was high, and since the connector was not directly related to the manipulator operation, the battery was replaced only once.

Tool Pick-up and Stowage

These tasks, each occurring twice, are the simplest of the entire sequence. Generally, they were performed with direct vision only, supplementary TV being unnecessary. Times were shorter than for any other task except for configuration C (Figure 8) where, almost without exception, each subject took considerably longer than with direct vision. The difference is much more pronounced than for any other task.

Since camera 1 was located on top of the manipulator boom and the end effector must be pointed downward to pick up or stow the tool, and since camera 5 did not view the tool stowage location, only cameras 2, 3 and 4 could be used for these tasks. Examination of Figure 2 shows that all three of these cameras view the stowage location from an oblique angle (relative to the boom in pick-up position) and that the angle is approximately the same for all three cameras. In addition, cameras 2 and 3 are opposite each other so that they provide essentially the same position information to the operator. Thus, the operator has three closely similar views (if he uses all three cameras), none of which is orthogonal to boom coordinates. The result is that the operator must concentrate to an excessive degree to be able to use the information presented.

Test subject "I" achieved the most consistent times with and without direct vision; his technique was to use only one camera, thereby eliminating the difficulty of associating each view with the correct viewpoint. This

subject was one of the most experienced of the entire group and as a result was better able to perceive and utilize relatively subtle cues (shadows, reflections, etc.) to determine position along the line of sight. Normally a second camera viewing at right angles to the first is preferred for accurate location and orientation in three dimensions. In this case, the simplicity of the task and the tolerance built into the jaws made precise positioning unnecessary.

Pin Locking and Release

These tasks were relatively simple. Times for configuration A were longer because accurate, three-axis orientation was required to place the tool over the head of the pin, and because about one minute of rotation was necessary after the tool was in place. This configuration was designed by GSFC especially for this test, as has been noted elsewhere in this report. It does not represent a flight item design. Tool alignment was not easy to perceive, and consistently good alignment was best obtained by setting pitch attitude with camera 3 on close-up, then leaving it undisturbed (the manipulator automatically maintains pitch attitude relative to horizontal) while adjusting yaw and roll for each pin using camera 1, also on close-up. The learning curve was short, and time per pin quickly stabilized at slightly less than three minutes (see Figure 9).

Configuration B proved much faster. Learning was fairly quick. Although the tool had to be positioned within ± 0.6 inch laterally, visibility with camera 1 was good and positioning was not a problem. Compressing both parts of the head, then sliding off (generally downward) while maintaining pressure was a fairly delicate operation, but did not appear to offer any real obstacle to any of the subjects. Considerable difficulty was experienced with pin number 3, which was harder to lock than the others as the result of a slightly oversize spring. This is reflected in the abnormally high times for pin 3 in both configurations B and C.

The primary problem encountered in this task was accidentally dropping the tool. This was caused for the most part by the position of the jaw-open button next to the roll and yaw control switch, the ease of actuation of the button, and the tendency of some operators to use the left hand to actuate both controls.

Module Extraction

The distribution of module extraction times, illustrated in Figure 10, shows two distinct groupings: a cluster of rapid extractions, many of which took less than 20 seconds, and a broad scattering of slower times

ranging up to six minutes or more. A second distinctive feature is the fact that lack of direct vision (configuration C) did not cause markedly higher times as in most other tasks. Both of these characteristics are best understood in terms of the module/spacecraft physical interface.

When the module is fully seated in the spacecraft, a pronounced wedging occurs at the conical surfaces. The breakaway force necessary varies with seating velocity and no systematic measurements were made; however, on a number of occasions the manipulator jaws, which have a known pulling capacity in excess of 50 pounds, slipped off the grappling fixture without unseating the module. As long as the module did not tilt, friction after initial unseating was very low. Since it is difficult to apply a high force and then to stop immediately when the force is not needed, most subjects tended to continue pulling after unseating. This resulted in nearly instantaneous extraction if the pull was straight enough to avoid tilting, and a hard jam if the module did tilt. In the latter case, the subject could usually free the module by pushing it back into the spacecraft. In a few instances, the module had to be freed manually. The problem was compounded by the tendency of some subjects to seat the module hard on insertion; these tended to be the same ones who tried to unseat and extract in a single motion.

Visual cues were normally of minor importance in this task. If the module jammed, TV was helpful in determining the direction of tilt, and therefore the direction to push in order to free the jam. Otherwise, incipient jamming could be better detected by feel (through force feedback) and there was no other alignment requirement in this task. Since vision was relatively unimportant, the lack of it did not impair performance.

Task Times - Configurations D, E and F

Since only a small number of runs was made in these configurations, any apparent trends in the data are difficult to substantiate. This discussion must therefore be somewhat tentative in nature.

Configuration D

Two runs were made. Task times were generally substantially higher than configuration C, the only other set-up without direct vision. Both test subjects ("D" and "I") felt that the harsh lighting and deep shadows had an adverse effect on performance. Although the light was placed so that all critical areas were illuminated for this test, orbital operations could impose such constraints that some areas remained in shadow, a condition that would not be tolerable without adequate supplementary illumination.

Configuration E

One run was made by subject "D" and one untimed run by the test director. Module insertion and extraction are the only tasks affected by grappling fixture location; no others will be discussed here. Subject "D" did not compensate for the off-center grappling point, resulting in binding during insertion. He was able to clear the jam, however, and complete the task. Extraction was accomplished without difficulty. The test director applied the insertion force roughly along a line between the grappling point and the center of the module, and insertion was completed without binding. It is concluded that although eccentric grappling points can be tolerated in operations of this kind, they should be avoided where possible.

Configuration F

Subjects "D", "E" and "I" used this configuration. It was anticipated that the floating, tethered spacecraft would create problems, but none developed. All three subjects achieved insertion times of two or three minutes. It is possible that the flexible mounting helped to the extent that it could, at least partially, compensate for any tendency to bind in yaw. There are, however, no specific data to support this hypothesis.

Pin locking required a different technique if large excursions of the spacecraft were to be avoided. This involved a sudden thrust once the tool was in position, rather than steady pressure, so as to utilize the inertia of the spacecraft and module. This method was not necessary for completion of the task, however.

It is concluded from this test that a flexible spacecraft support would not be detrimental to satellite servicing operations.

MAN-MACHINE ENGINEERING

General

The objective of this portion of the study was to examine several man-machine engineering factors affecting manipulator design and to identify man-machine engineering design guidelines for the Shuttle manipulator system.

The primary areas evaluated were task analysis, operator/manipulator visual system assessment, and subjective comments.

Commitments to priority work sharply curtailed the effort that could be devoted to this study. As a result, this analysis deals only with the early runs (configuration A).

Task Analysis

A task analysis approach was utilized to reduce the overall job to elemental tasks, which could be more easily handled in evaluating subject performance, information requirements, etc. The following tasks were identified:

1. Pick up boom and align with module
2. Grapple module
3. Align module for insertion
4. Insert module completely
5. Retrieve, align and insert tool
6. Tighten pin 1
7. Realign boom
8. Tighten pin 2
9. Realign boom
10. Tighten pin 3
11. Realign boom
12. Tighten pin 4
13. Deposit tool
14. Retrieve, align and insert tool
15. Loosen pin 1
16. Realign boom
17. Loosen pin 2
18. Realign boom
19. Loosen pin 3
20. Realign boom
21. Loosen pin 4
22. Deposit tool
23. Grapple module
24. Remove and release module

A preliminary analysis produced the following initial conclusions:

- a. The module alignment task (i.e., alignment of all four corners of the module with the spacecraft) was the most difficult task to accomplish, as measured by performance time, amount of information (perceptual cues) and operator skill required.
- b. The module alignment task was facilitated by the use of TV, especially when orthogonal camera views were selected.

- c. Alignment of the left side of the module seemed more difficult than the right side; the subject's viewing angle, which had restricted visual access to the left side, may have been the cause.

Operator/Manipulator Visual System Assessment

One of the major areas of evaluation during this test period was the operator/manipulator visual system. The system evaluation addressed three specific questions: (1) how much of the time does the operator use TV and how much looking directly at the task being performed, (2) which TV cameras are used by the operator to assist in task performance, and (3) what can be said about the operator workload (i.e., task performance demands on the operator)? At the same time, the evaluation attempted to identify preliminary man-machine engineering design guidelines for application to the Shuttle manipulator system.

For the assessment, video tape recordings of the runs of six subjects were analyzed. The video-taped picture was identical to that selected by and appearing on the subject's upper TV monitor except for the lower left corner, upon which a picture of the subject performing the task was inserted. The recordings were complemented by observations by the man-machine engineering specialists made during these and other runs.

The first two questions above were addressed at the beginning of the study. A data analysis sheet was formatted and used to analyze the tape recordings. This sheet allowed various phases (see Task Analysis section above) or individual tasks for any one simulation run to be correlated with the total task time, time the subject spent looking at the TV monitors, and time the subject spent looking directly at the task being performed.

The percent of time spent by the subject watching the TV monitors and viewing the task directly was calculated from the data sheets as a function of total task time (i.e., time for one simulation run). The resulting data, shown in Table 3, indicate that the subjects spent an average of 73% of the total time viewing the task directly while using the TV system only 27% of the time. These percentages vary only slightly from one subject to another. Attempts to discern significant variations in the percentages of direct and TV viewing from one task to another were largely unsuccessful because of the scattered data obtained. An exception was tool stowage (tasks 13 and 22) for which 100% direct vision was almost universally used.

A further analysis indicated that cameras 1 and 3 were used most often by the subjects in gathering the necessary perceptual cues to perform the entire task. As can be seen by the diagram of camera locations (Figure 2), these cameras provide orthogonal views of the tasks required.

Three basic approaches were utilized to determine the answer to the third question above. The first approach made the assumption that the demand of the task on the operator could be measured by the time a subject spent fixating on either the TV monitor or the task. This time was designated as Eye Fixation Time (EFT). Subject EFT was obtained from the video-tape recordings. The following trends were observed:

- a. EFT, compared to total run time, was extremely high (above 80%) for all subjects.
- b. EFT was not a function of media used; that is fixation times were high whether the subject viewed the task directly or via TV.
- c. EFT was proportional to the task demand on the subject (i.e., to the number of perceptual cues or information required to perform the task).

The second approach involved a video tape analysis to determine what percentage of time a subject used his left hand to assist in manipulator operations (e.g., as a steadying device, or to adjust controls). This approach addressed the physical demand on the subject more than the mental loading. Results of tapes analyzed are shown in Table 4. The left hand was used during manipulator operations an average of 23% of the total run time.

The third approach in determining operator workload was through subjective ratings. When asked for a subjective degree of difficulty to perform one simulation run, the ratings shown in Figure 11 were given. Most of the subjects felt the total task was at least twice as difficult as driving a car on a crowded interstate highway.

Subjective Comments

Subjective evaluation questionnaires (Appendix D) were administered to fourteen subjects, each of whom completed the questionnaire at the end of his first simulation run. Most of the questions were concerned with procedures, hardware and simulation events. During the questioning, the subjects were encouraged to express themselves freely. No subject identification was placed on the completed questionnaire.

The following summarizes the subject's comments:

- a. **Test Objectives and Procedures**

Seventy percent of the subjects felt that the test objectives and procedures for the simulation were easily understood.

However, many subjects felt the pin loosen/tighten tasks needed additional detailed description. Also, many of the subjects expressed the desire to spend more time in reviewing the procedures prior to the initial simulation run.

b. Hand Controller Switch Functions

Although this study did not include an evaluation of the detailed manipulator hardware unique to this simulator (including design recommendations for hand controllers), the subjects generally remarked that the switch functions of the hand controller were not natural and needed improvement.

c. Relative Location of Hand Controller

Two thirds of the subjects felt that the hand controller height, relative to the operator seat, was too high for the forces required for manipulator operation.

d. Use of Arm Rest

Eighty-three percent of the subjects used the arm rest and stated the rest gave support in one-g. Although an arm rest providing this function in zero-g may not be required, one in zero-g may be required to provide stability for the arm.

e. Feedback Forces

Half of the subjects felt the manipulator feedback force was too high, while one third said the force was too low. Fourteen percent said the feedback force was at the right level. One subject was unaware of any feedback force. In all cases, subject concentration may have precluded them from being more attentive to the force feedback involved. However, eighty-three percent of the subjects felt that force feedback was a very important characteristic for manipulator operations.

f. Fatigue

Seventy-eight percent of the subjects experienced some form of physical fatigue from operating the manipulator. The fatigue was associated with the hand, wrist, arm, shoulder, and upper back. Force required to move the manipulator was stated as the major contributing factor of fatigue.

g. Seat Comfort

The subjects made no negative statements concerning the operator seat comfort. Lack of either positive or negative comments

indicates the subjects may have been too involved in the task being performed to have noticed whether the seat was comfortable or not.

h. Terminal Device Functional Design

All subjects interviewed stated that the terminal device (end effector) was straightforward in its functional design. However, sixty percent of the subjects felt that improvement in the end effector design was needed. No design suggestions were made.

i. Terminal Device Markings

Sixty-six percent of the subjects stated that color coding or increasing contrast between the end effector and module grappling fixture facilitated task performance for grappling the module.

j. TV Control Assessment

Eighty-three percent of the subjects thought the TV controls were conveniently located and their functions self-explanatory.

k. TV Picture Contrast

Increased contrast of the TV monitor picture was preferred by ninety-two percent of the subjects. (NOTE: Contrast level was set initially by the Test Conductor at the same level for all subjects.)

l. Illumination Level

Thirty percent of the subjects stated that the simulation lighting, in general, was inadequate.

m. TV Usage

Eighty-five percent of the subjects felt they did not maximize use of the TV system.

Test Observation

This section summarizes observations made by the man-machine engineering specialists during the test runs.

1. Subjects using camera 1 as the primary TV data source experienced more difficulty in pitch alignment during the module alignment task.

2. Marking the module corners and spacecraft rails for increased contrast contributed significantly in facilitating completion of the module alignment/insertion tasks.
3. Illumination, task background, noise and perceptual cues are important parameters for inclusion into realistic simulations.
4. Audio cues (e.g., banging module against fixture) facilitated the module alignment task.
5. TV capability (i.e., pan, tilt and zoom) was fully utilized by all test subjects, although use of the TV system was not optimum.

CONCLUDING REMARKS

Most of the objectives of this simulation were achieved; all were at least partially accomplished. However, the physical limitations of the test set-up and the specific nature of the task restrict the extent to which the results may be generalized.

1. Replacement of modular components by manipulator is feasible.
2. The eccentric grappling point was usable, but a central location is preferred.
3. The spacecraft being serviced could be supported by a second manipulator boom.
4. The automatic umbilical connector operates satisfactorily.
5. The end effector and grappling fixture were usable, but could be improved (see Manipulator Design below).

Many of the specific conclusions that follow are little more than good engineering practice and common sense, and are mentioned because they were emphasized by the test.

Operator Vision

Operator vision, both out-the-window and TV, is a crucial aspect of manipulator system design. Both this and previous simulations indicate that the operator's ability to see the task, not the capability of the manipulator itself, is generally the limiting factor in system performance.

TV camera lines of sight aligned with the manipulator coordinate system appear to be more easily utilized by the operator in determining required directions of motion. The number of cameras required, camera locations and camera performance are major parameters that require detailed investigation.

Television alone can be used to perform difficult tasks, but every test subject who tried it preferred direct vision plus TV to TV alone. A major problem was obtaining an adequate sense of boom position without the direct view. It is concluded that windows should provide a direct view of manipulator operations.

Work site lighting should be arranged to illuminate all shadowed areas. However, care should be taken to avoid distracting reflections from polished surfaces, either by light source location or by using dull finishes in critical areas.

Manipulator Design

A fundamental result of this test is that fatigue can be a problem in lengthy, exacting operations. Part of the fatigue resulted from characteristics of the CAM 1400 manipulator that would not exist in a flight system, but part was also caused by the high level of concentration, the very small, controlled arm movements required, and the length of time required to complete a run. While it may be assumed that the astronaut operating the Shuttle manipulator will be better able to tolerate these stresses than most of the test subjects, the likelihood of fatigue must be considered both in manipulator control station design and in mission planning involving extensive manipulator operations.

Although no runs were attempted without force feedback, it is believed that feedback is essential for reliable insertion and extraction of this module, since it provided the principal sensory input for these operations. It also follows that a rate control system would be inefficient for these tasks, and perhaps unusable.

On a number of occasions, the operator dropped the tool accidentally, left the tool on a pin head, or lost his grip on the module. It will be necessary on the Shuttle to provide tethers or appropriate safety devices on the controls to positively prevent loss of tools, modules, etc.

End effector design has a substantial impact on the efficiency of the manipulator. The end effector used for these tests had insufficient clearance for easy grappling, the torque capacity was too low in some axes, and the jaws could be pulled free of the grappling fixture by a rapid motion.

Servicing a satellite held by a second manipulator boom or other slightly flexible support appears feasible.

Payload Design

The positioning tolerance of $\pm 1/4$ inch required for this module is too small to assure consistent performance. To provide a better margin for error and to allow for the larger master/slave size ratio that will probably exist on the Shuttle, ± 1 inch is suggested as a preliminary minimum standard pending more definitive simulation results.

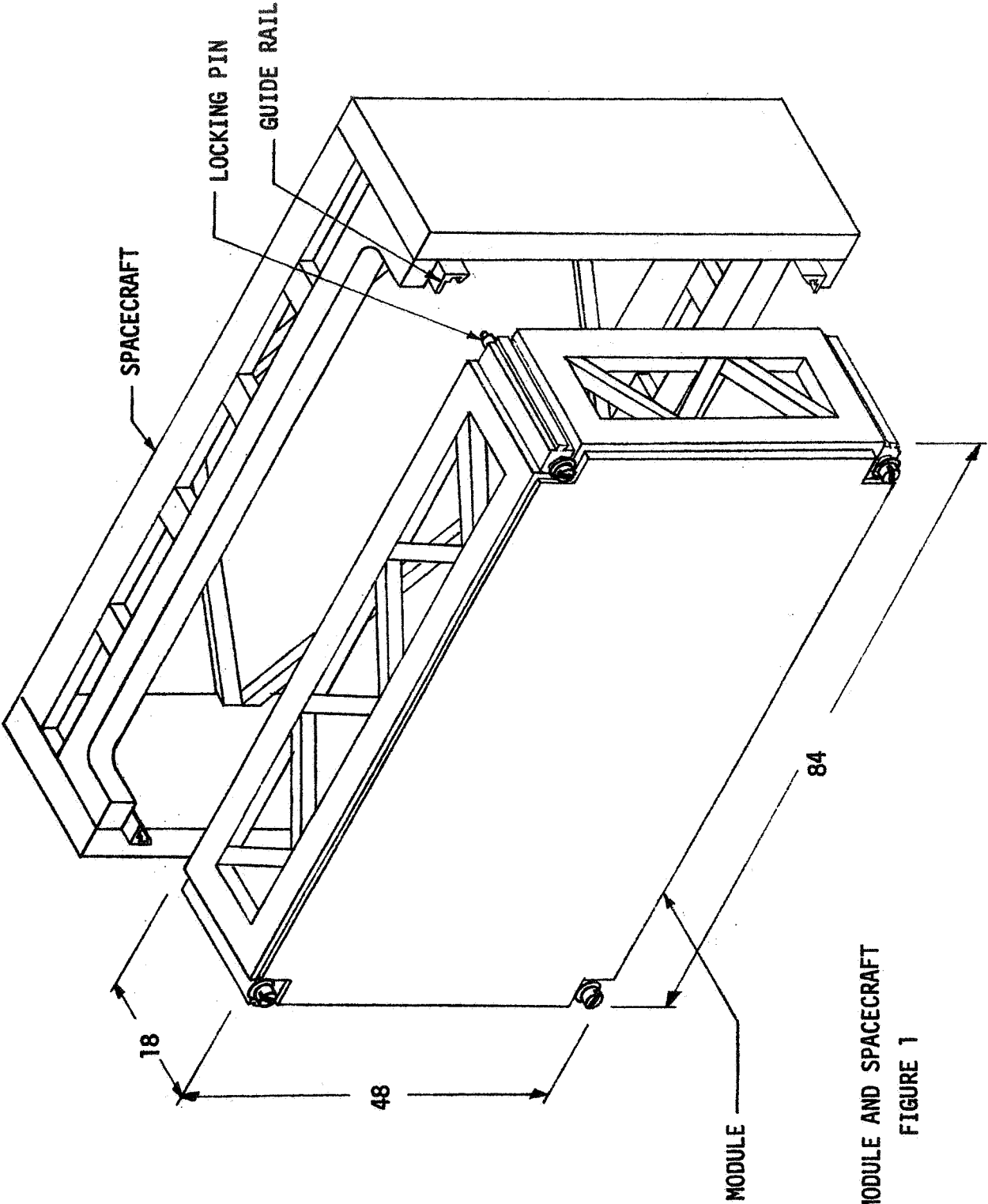
The close-tolerance rails used on this module should be avoided. Many of the jams that occurred during the tests could have been cleared in orbit only by EVA.

The limited force capability of the boom should be considered in the design of mating parts, latch actuators, etc. If necessary, special end effectors could be used to match the capability of the boom to the requirements of the payload.

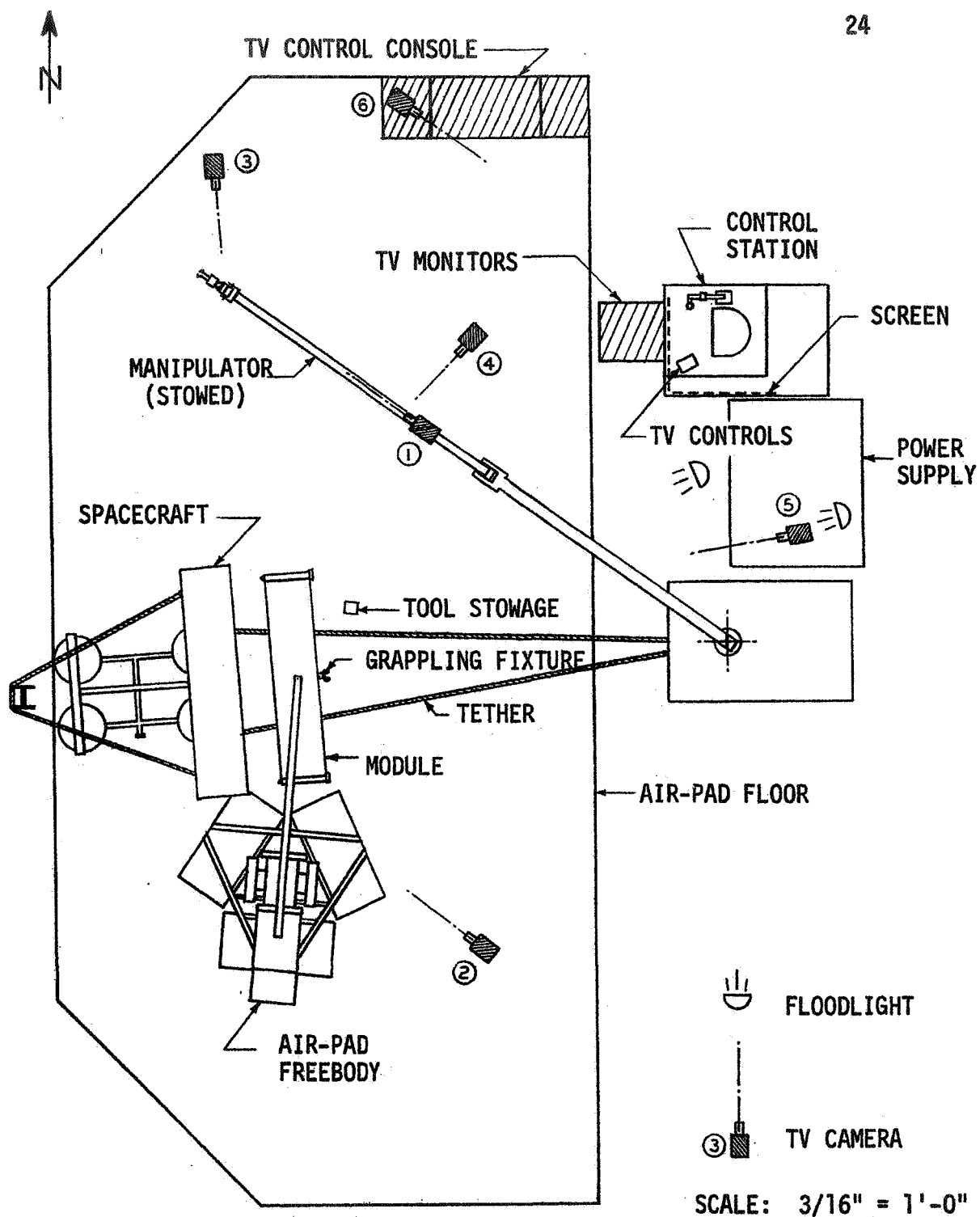
Locks, latches, etc. to be operated by the manipulator should provide indication of positive latching and unlatching to the manipulator operator.

REFERENCES

1. "Attached Manipulator System Simulation Plan," MSC Internal Note 72-EW-6, March 1972 (MSC-07009).
2. "Attached Manipulator System Simulation 1 - Grappling a Fixed Object," MSC Internal Note 72-EW-7, December 1972 (MSC-07643).
3. "Experiments Evaluating Compliance and Force Feedback Effect on Manipulator Performance," General Electric Co., Contract NAS9-12536, 25 August 1972 (MSC-07239).

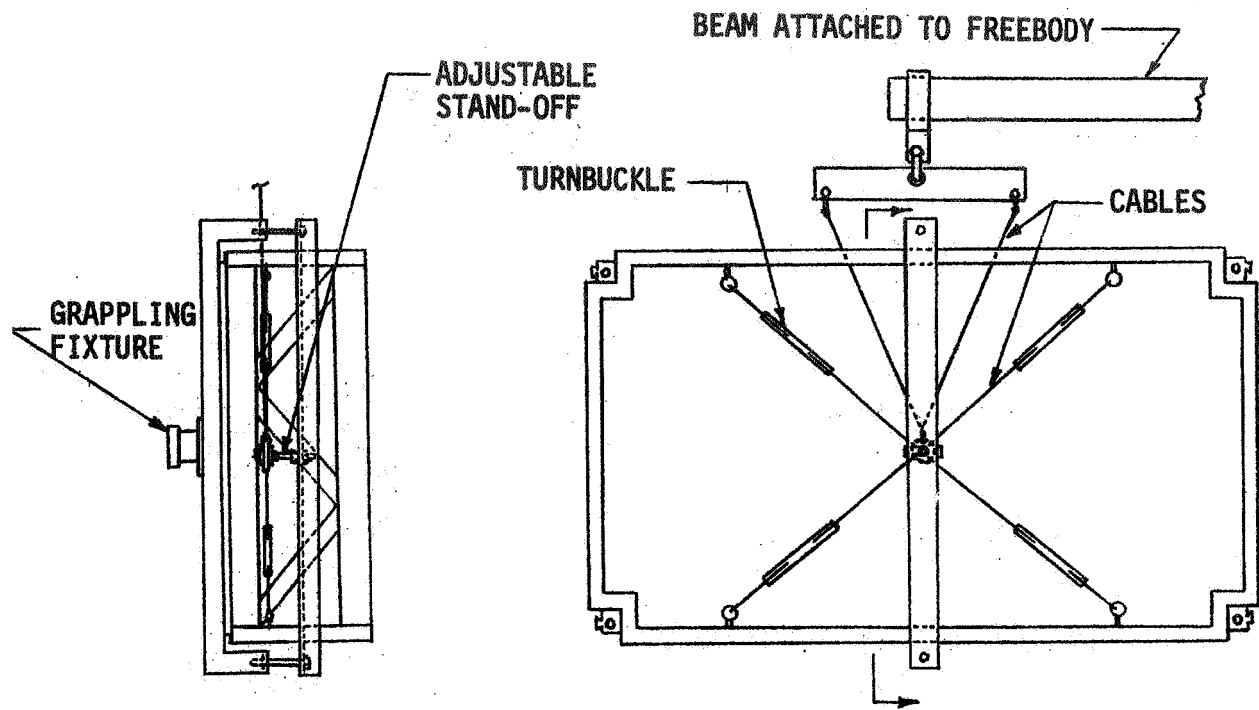


MODULE AND SPACECRAFT
FIGURE 1



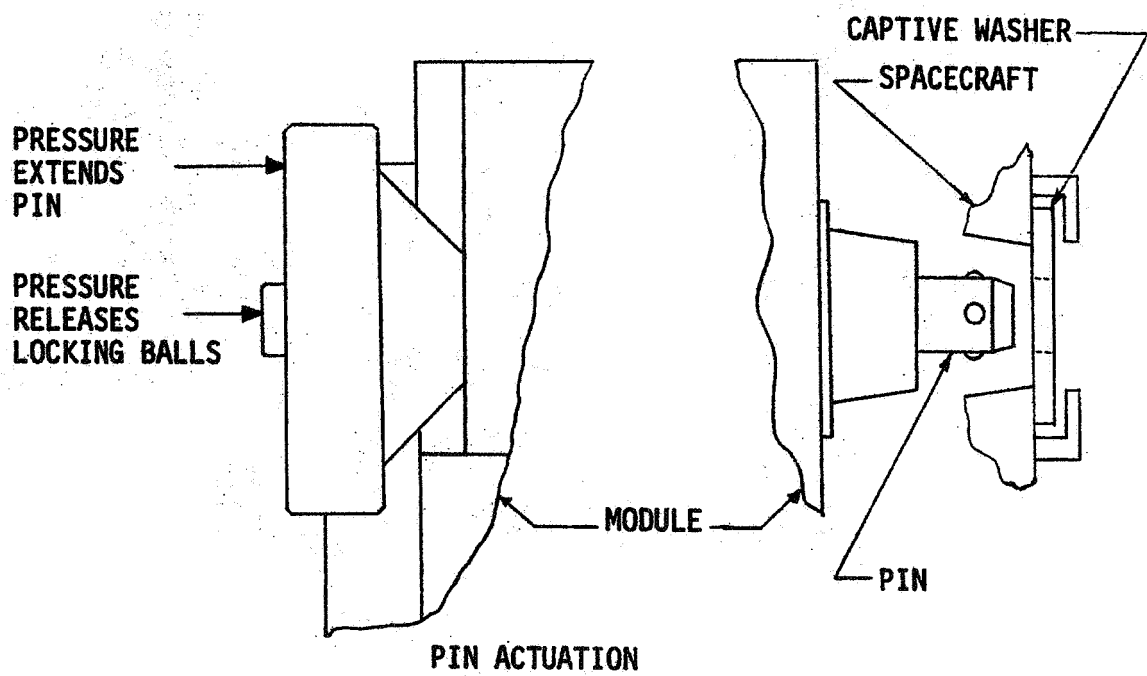
TEST SET-UP

FIGURE 2



MODULE SUSPENSION

FIGURE 3



PIN ACTUATION

FIGURE 4

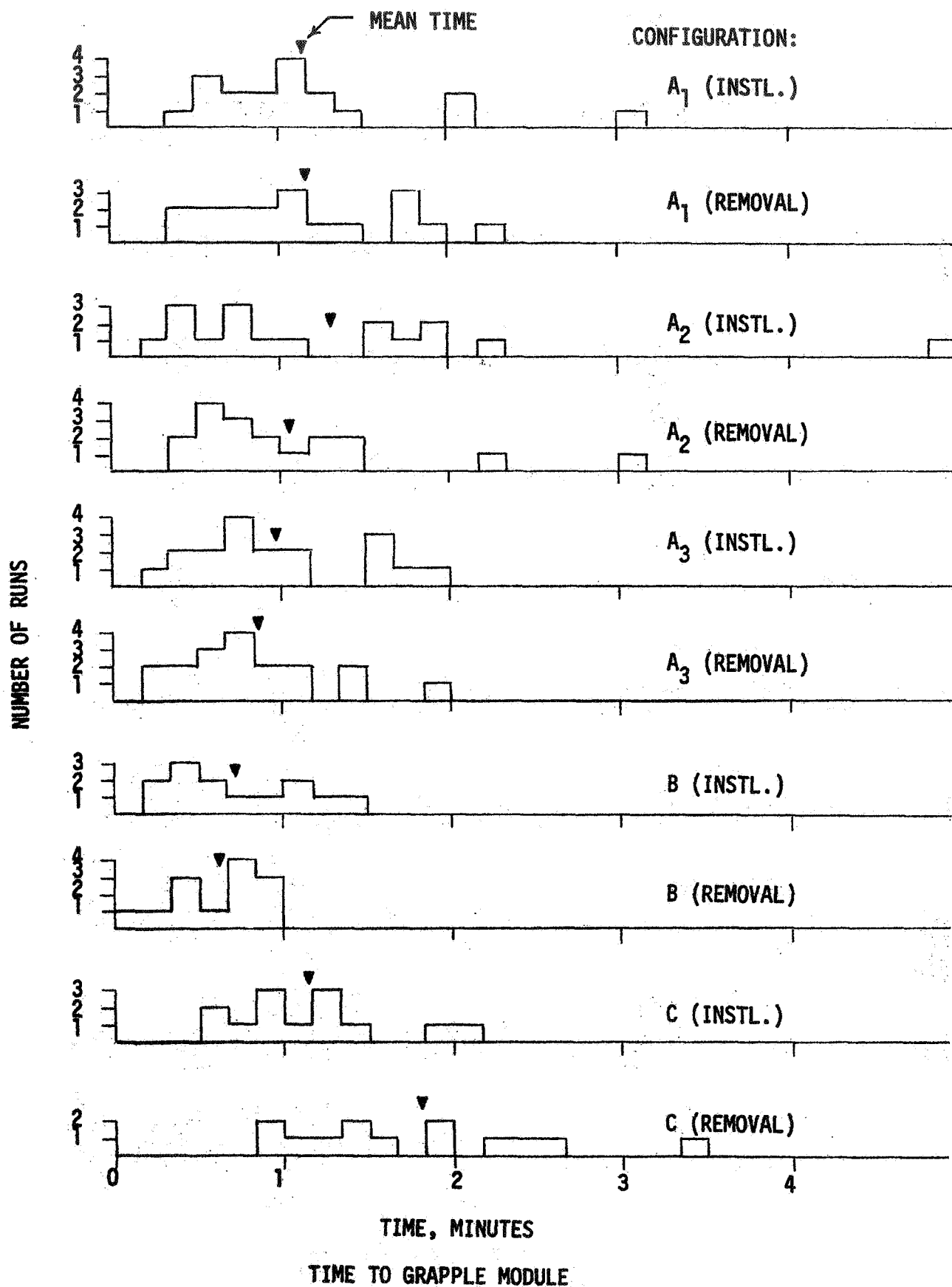
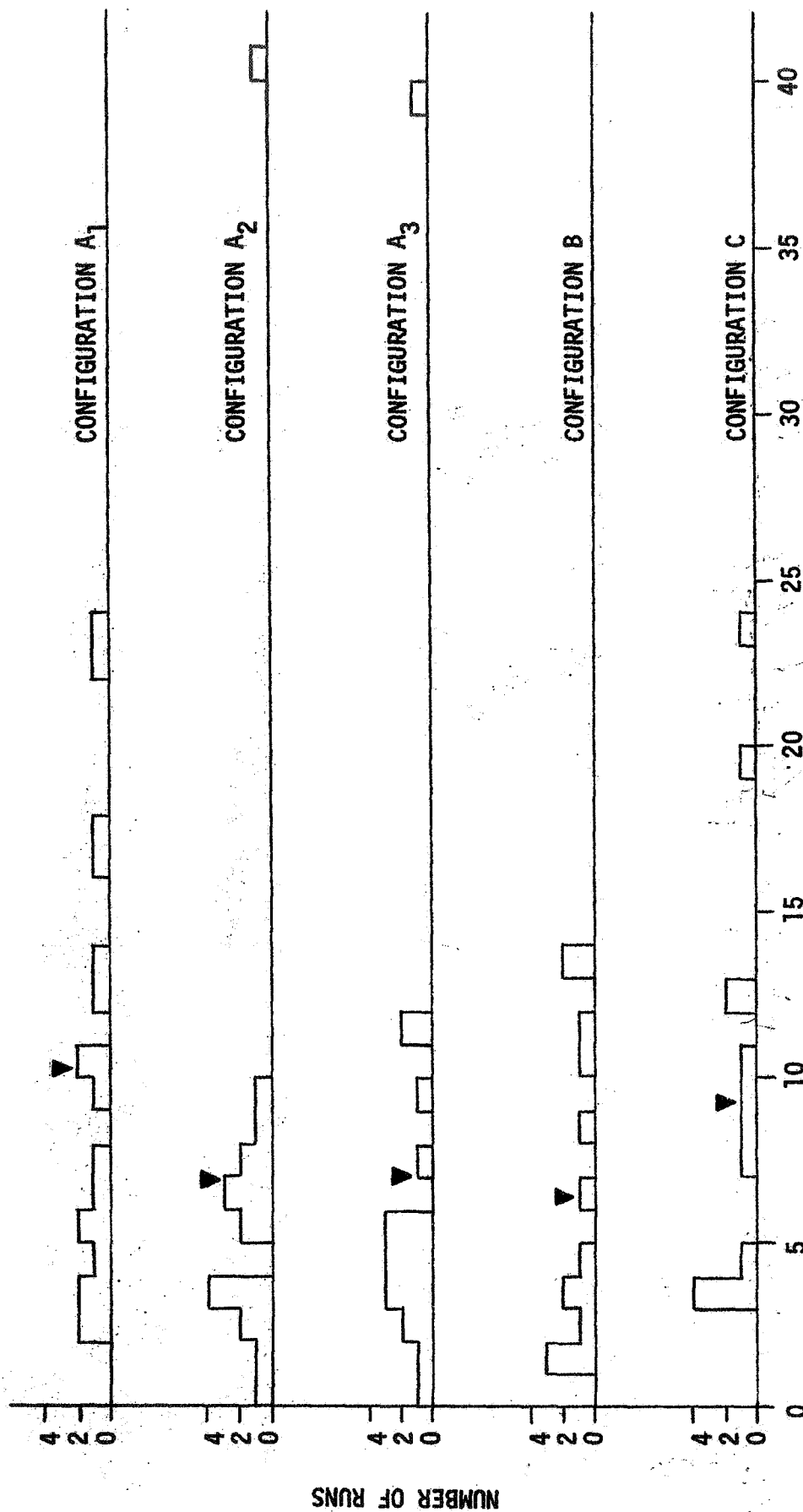


FIGURE 5

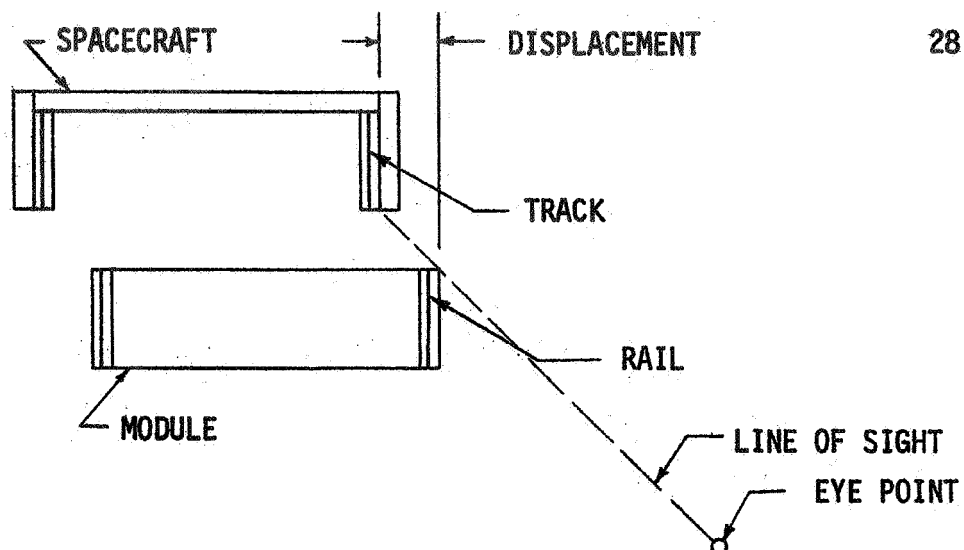
▼ -- MEAN INSERTION TIME



TIME TO INSERT MODULE IN SPACECRAFT, MINUTES

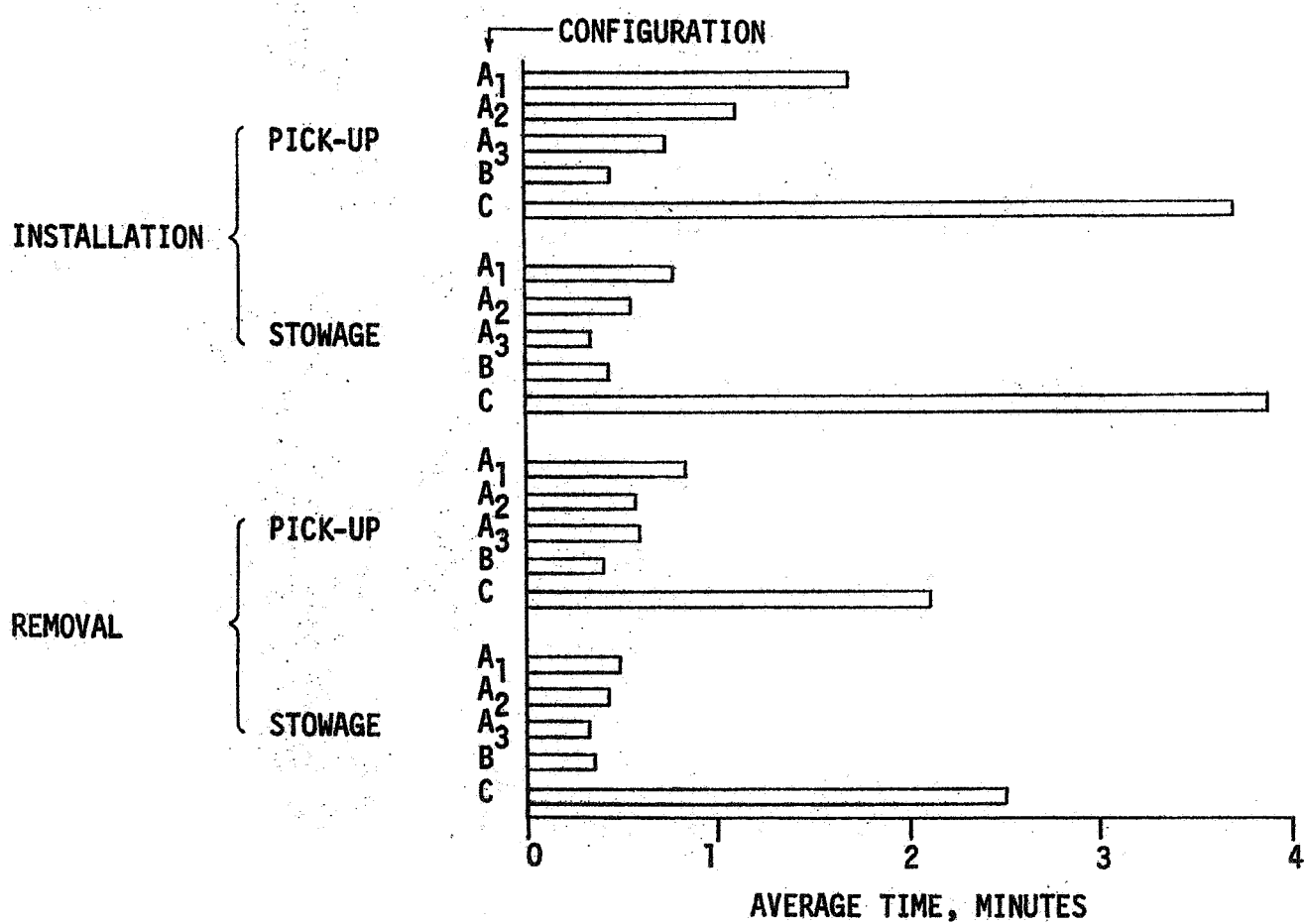
MODULE INSERTION TIME DISTRIBUTION

FIGURE 6



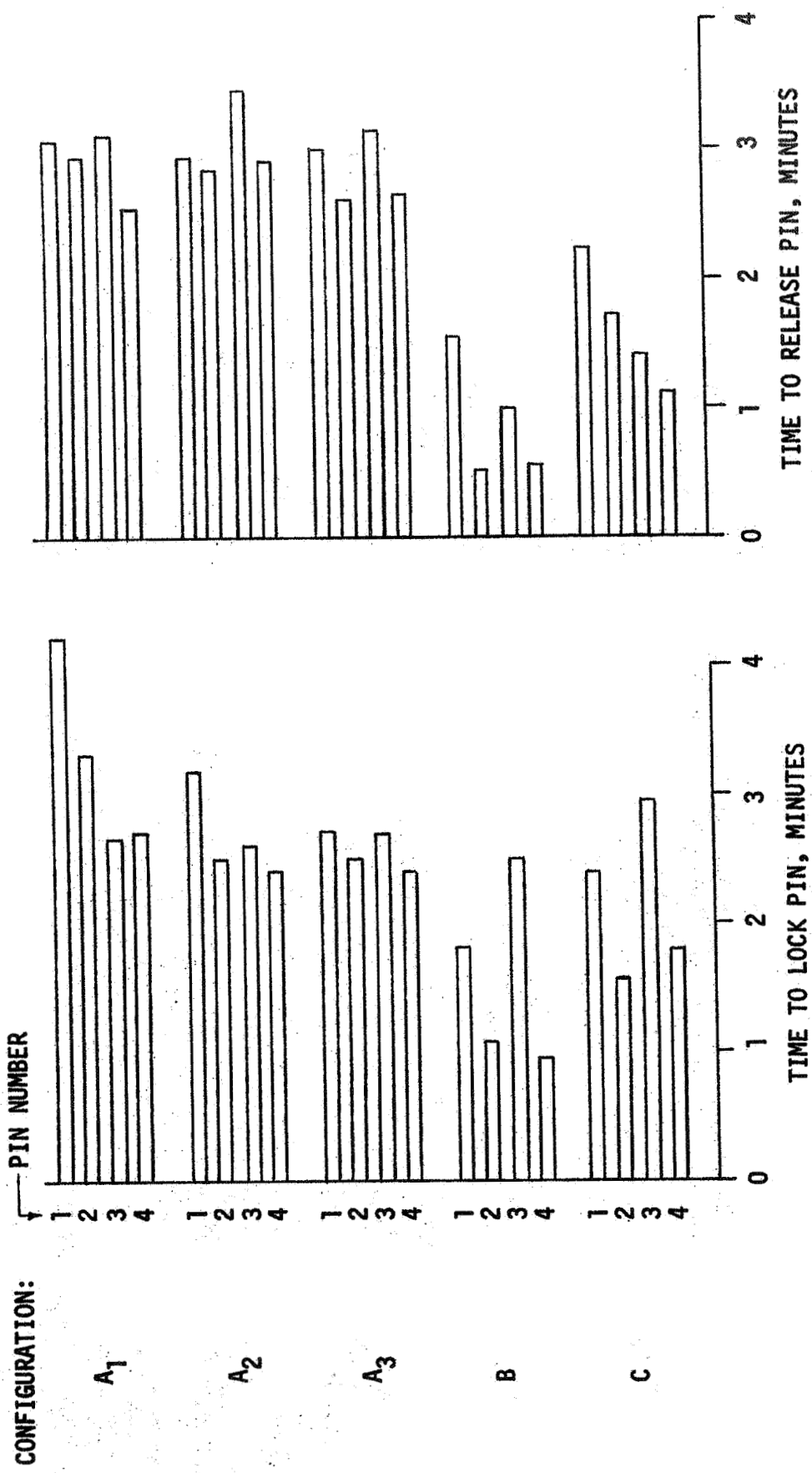
LATERAL DISPLACEMENT OF MODULE

FIGURE 7



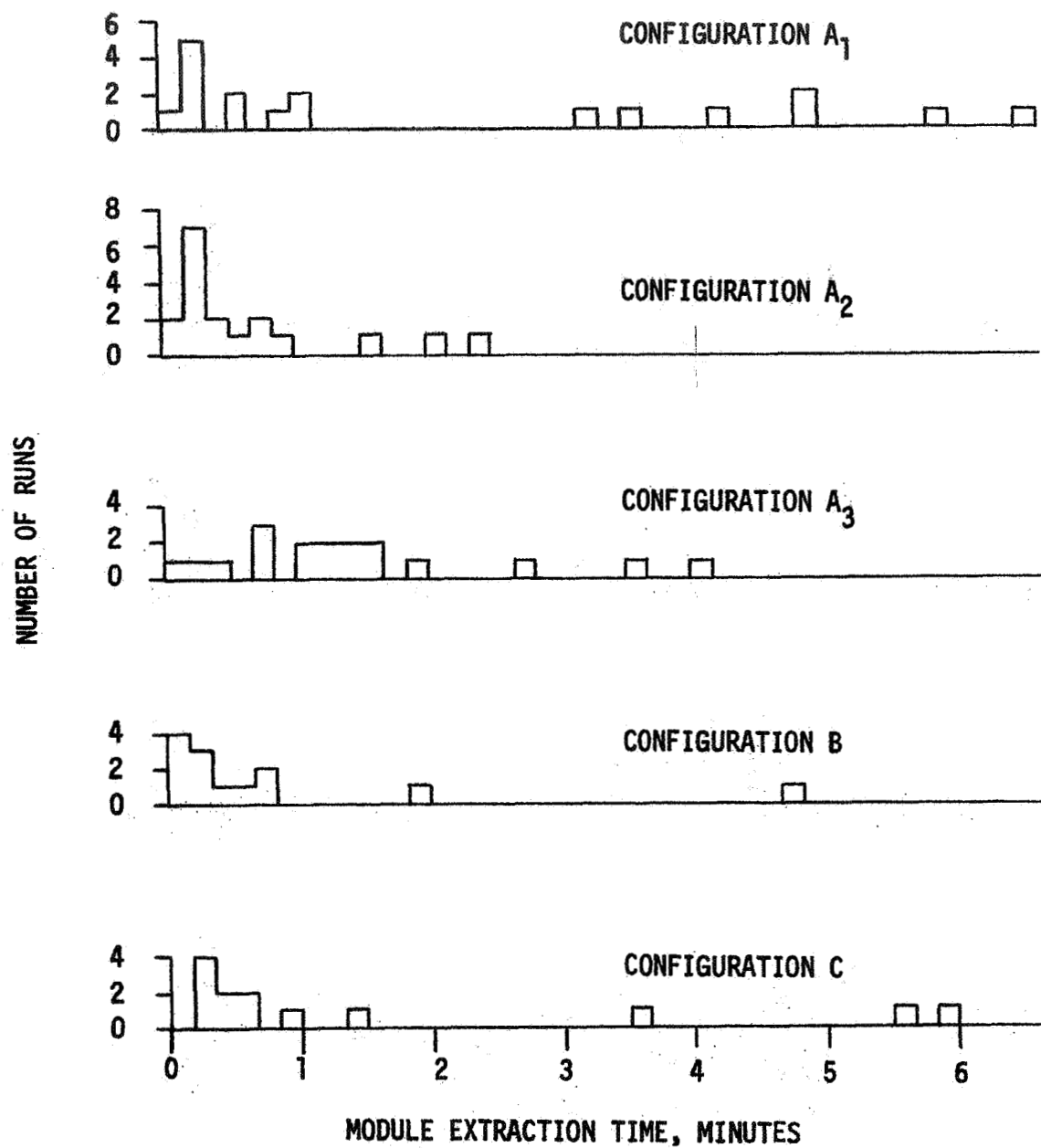
TOOL PICK-UP AND STOWAGE TIMES

FIGURE 8



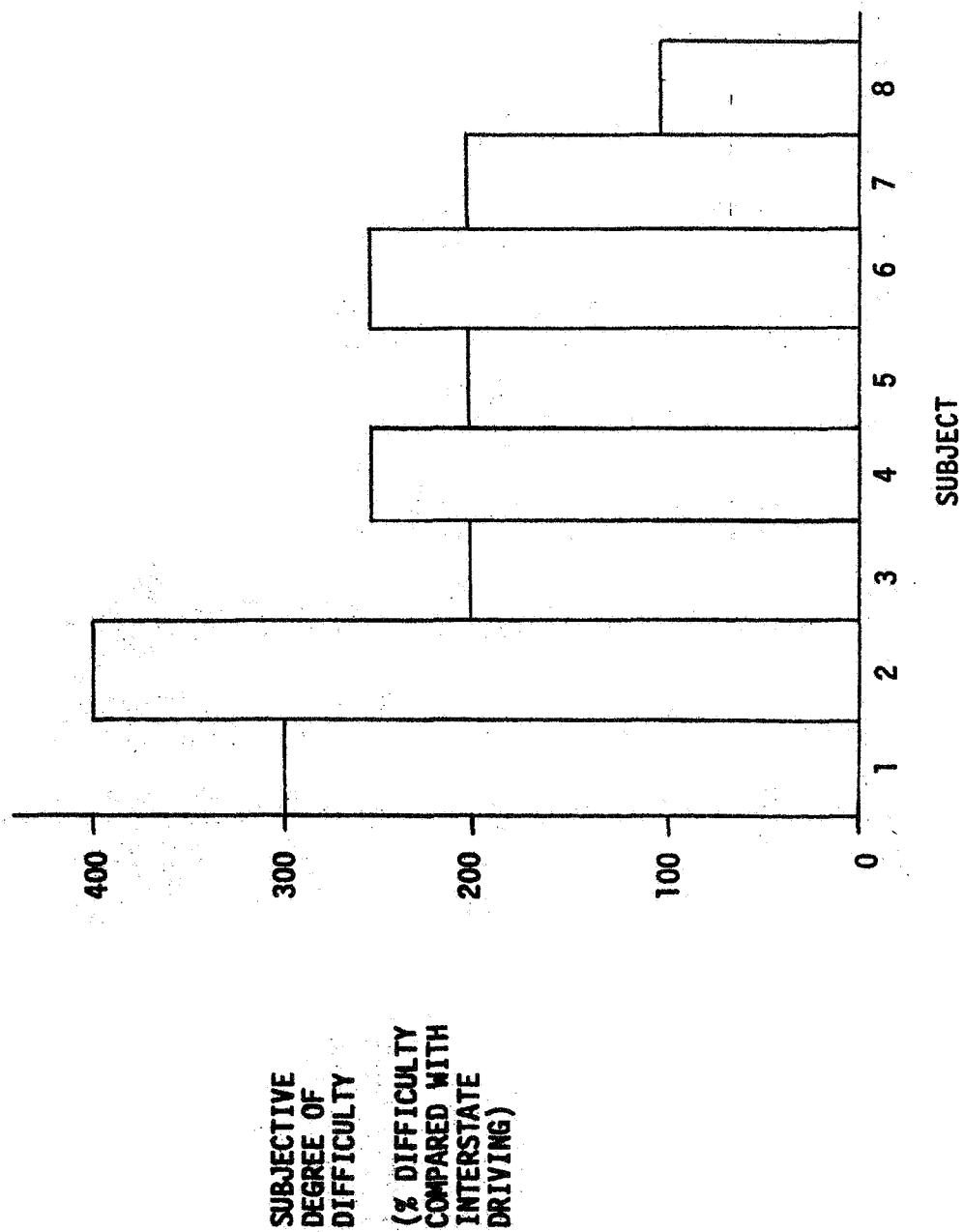
PIN LOCK AND RELEASE TIMES

FIGURE 9



MODULE EXTRACTION TIME DISTRIBUTION

FIGURE 10



SUBJECTIVE RATING OF TASK DIFFICULTY

FIGURE 11

TABLE 1

TEST CONFIGURATIONS

CONFIGURATION	PIN LOCKING MECHANISM	GRAPPLING FIXTURE LOCATION	SPACECRAFT	VIEWING	ALIGNMENT AIDS	LIGHTING	NUMBER OF RUNS
A	Screw Activated	Center	Fixed	Direct and TV	None	Ambient and Fixed Flood	54
B	Push Activated	Center		Direct and TV	None	Ambient and Fixed Flood	14
C		Center		TV Only	Taped edges on module & spacecraft	Ambient and Fixed Flood	13
D		Center		TV Only	"	Fixed Flood	2
E		Corner	Fixed	Direct and TV	"	Ambient and Fixed Flood	1
F	Push Activated	Center	Floating	Direct and TV	"	Ambient and Fixed Flood	3

TOTAL

87

TABLE 2

TEST SUBJECT EXPERIENCE

<u>SUBJECT</u>	<u>CAM 1400 EXPERIENCE, HOURS</u> <u>START OF RUNS</u>	<u>END OF RUNS</u>	<u>NO. OF</u> <u>RUNS</u>	<u>SIM. 1 - GRAPPLING</u> <u>FIXED OBJECT</u>	<u>COMPLIANCE &</u> <u>FEEDBACK TESTS</u>
A	5.0	8.3	5	X	X
B	1.6	4.0	3	X	
C	6.5	9.3	5	X	X
D	7.8	11.3	8	X	X
E	1.9	3.8	4	X	
F	2.0	4.6	5	X	
I	6.5	8.9	7	X	X
J	1.5	5.3	5	X	
K	1.8	4.4	3	X	
L	1.7	5.4	5	X	
M	0	2.6	5		
N	0.3	3.4	5		
O	0.7	2.5	3		
P	0.7	3.5	5		
Q	0	3.9	5		
R	0.3	3.1	5		
S	0	3.4	3		
T	0	3.6	5		

TABLE 3

TASK TIME ALLOCATION

<u>SUBJECT</u>	<u>TOTAL TIME (SEC)</u>	<u>TV VIEWING (% OF TOTAL)</u>	<u>DIRECT VIEWING (% OF TOTAL)</u>
C	2889	34	66
K	2153	21	79
E	2157	30	70
I	<u>1462</u>	<u>23</u>	<u>77</u>
Average	2165	27	73

TABLE 4

USE OF LEFT HAND

<u>SUBJECT</u>	<u>TASKS</u>	<u>TIME HAND USED</u>	<u>% TOTAL RUN TIME</u>	<u>TOTAL RUN TIME</u>
1	Pitch Control TV Zoom/Pan/Tilt TV Select "Groping" For Pitch Control	2 min.	7	25 min. 4 sec.
2	TV Zoom/Pan/Tilt TV Select Hand Control Support	9 min. 1 sec.	42	21 min. 5 sec.
3	TV Pan/Tilt TV Select Hand Control Support	6 min. 58 sec.	29	23 min. 26 sec.
4	TV Zoom/Pan/Tilt TV Select	4 min. 11 sec.	14	28 min. 14 sec.
	Average		<u>23</u>	

APPENDIX A

CAM 1400 Simulation 2Detailed Test Procedure1.0 INTRODUCTION

This detailed test plan describes the test to be conducted during the attached manipulator system simulation 2A.

The test is being conducted in compliance with requirements set forth in MSC-07009, Attached Manipulator System Simulation Plan.

2.0 OBJECTIVES

See page A2-1, MSC-07009.

3.0 TEST PERSONNEL RESPONSIBILITIES

a. Test Director (TD)

The TD is responsible for management, safety, subject indoctrination, test conduct, data acquisition, data evaluation and preparation of test report.

b. TV Coordinator

The TV coordinator is responsible for seeing that all TV cameras and supporting equipment are available and functioning as directed by the TD.

c. Test Technician

The test technician is responsible for insuring that the free body functions as required during the test.

4.0 TEST CONDITIONS

The module, female check fixture, manipulator, screwdriver attachment, cameras and lighting shall be prepositioned at designated location prior to each test run.

The manipulator, freebody and TV equipment shall be activated prior to beginning of each test.

The TD shall be furnished a microphone for recording test events on video tape.

5.0 SAFETY CONSIDERATIONS

See Section 8.0 of MSC-07009.

6.0 DETAILED TEST PROCEDURES

Pre-Test Setup

1. Activate Freebody

- (a) Turn handle on shop air valve CCW to fully open.
- (b) Turn variacs #4, 5 and 6 to zero.
- (c) Turn power switch #4 to ON.
- (d) Turn variac #4 CW until meter indicates 100 volts.
- (e) Repeat steps (c) and (d) for variacs #5 and 6.
- (f) Check pressure regulator indicator to verify it reads approximately 70 lbs.
- (g) Visually align yellow markings on the air piston cylinder by adjusting handle on pressure regulator valve. Adjust as required to maintain alignment throughout the test run.
- (h) If circuit breaker trips during operation, turn power switches 4, 5 and 6 to OFF before resetting circuit breaker, then repeat steps (b) through (e).

2. Activate TV System

- (a) Turn all TV power switches to ON. (One switch per rack).
- (b) Remove lens caps from all cameras.
- (c) Adjust cameras if necessary.

3. Seat Test Subject

- (a) Seat subject

4. Activate CAM 1400

- (a) Turn on main circuit breaker.
- (b) Grasp control handle in right hand.
- (c) Turn on CAM 1400 (black button under left front corner of seat).
- (d) Immediately move control handle to match boom position (full right against azimuth stop, shoulder full down, elbow such that end effector is on floor at maximum extension) while pressure is building up. Any position mismatch can be detected as a hissing sound in the boom.
- (e) When full pressure is reached, slide the boom toward its base until the pitch actuator is at the edge of the wooden stowage pad nearest the base. Then slowly raise the boom clear of the pad until the boom is full controllable.

5. Install Module

- (a) Grapple module with manipulator end effector.
- (b) Align module with female fixture.
- (c) Insert module into female fixture.
- (d) Fully seat module by having end of module rails flush with the female track end surface.
- (e) Release module by removing end effector from module.
- (f) Pick up wrench attachment from floor.
- (g) Insert wrench attachment in pin on module.
- (h) Fully seat wrench attachment in pin.
- (i) Rotate wrench attachment one (1) full turn CCW.
- (j) Repeat the above three steps for each of the remaining three pins.

- (k) Place wrench attachment on floor after all four pins are secured.
- (l) Stow manipulator.
- (m) Take a five minute break.
- (n) Check to see that all four pins are locked. If not, lock them.

6. Seat Test Subject

- (a) Seat subject.

7. Activate Manipulator (Same as 4.0 above).

8. Remove Module

- (a) Pick up wrench attachment from floor.
- (b) Insert wrench attachment in pin on module.
- (c) Fully seat wrench attachment in pin.
- (d) Rotate wrench attachment one (1) full turn CW and remove from pin.
- (e) Repeat the three above steps for each of the remaining three pins.
- (f) Place wrench attachment on floor after all four pins are released.
- (g) Grapple module with manipulator end effector.
- (h) Pull module free from female fixture.
- (i) Release module and move boom clear.

9. Shutdown

- (a) Stow boom on wooden stowage pad at full horizontal extension and extreme right azimuth.
- (b) Shut down manipulator (red button at left of seat).
- (c) Insure that module is clear of check fixture, then turn off switches 4, 5 and 6 on freebody control console.

- (d) Turn variacs 4, 5 and 6 fully counterclockwise.
- (e) Reset cameras to standard positions if necessary.
- (f) Turn off manipulator master circuit breaker.
- (g) Turn off all TV equipment racks (5 switches).
- (h) Place lens caps on TV cameras.
- (i) See that all four pins are turned fully clockwise.
- (j) Reposition female check fixture to index marks on floor (if necessary) by turning on shop air valve slightly to float fixture.
- (k) Turn off shop air supply valve (fully clockwise).

APPENDIX B

InstructionsSimulation 2

The primary objective of this simulation is to demonstrate the feasibility of using a manipulator to replace a subsystems module of an unmanned orbiting spacecraft. Secondary objectives are to study the operator's utilization of the visual and TV cues available to him, evaluate the suitability of the terminal device used, and identify problem areas associated with this task.

At the beginning of the test, the module (gold-colored) will be floating free of the female check fixture (aluminum) which represents the spacecraft. At the "Go" command from the test director, proceed as follows:

1. Activate the boom.
2. Grapple the grapping fixture at the center of the module back panel.
3. Maneuver the module into alignment with the check fixture using any combination of direct vision and TV cameras you wish.
4. Insert the module all the way into the check fixture until the ends of the corner rails are flush with the ends of the tracks in the check fixture.
5. Release the grapping fixture and pick up the wrench attachment on the floor.
6. Place the wrench over the screw head at a corner of the module, aligning the white tapes on the wrench with the ends of the slot in the head. Accurate alignment is necessary for complete engagement of the wrench.
7. While maintaining engagement, rotate the wrench counter-clockwise at least one full turn. Insure that the module remains fully inserted during this operation.
8. Remove the wrench from the screw head.
9. Repeat steps 6, 7 and 8 at the other three corners of the module.
10. Place the wrench at its stowage position on the floor.
11. Stow the boom.

To remove the module from the check fixture, the procedure is reversed:

1. Activate the boom.
2. Pick up the wrench.
3. Rotate the four screw heads clockwise as far as possible.
4. Put down the wrench.
5. Grapple the module grapping fixture.
6. Pull the module free of the check fixture and bring it to rest.
7. Release the module.
8. Stow the boom.

Appendix C

TEST DATA

This appendix tabulates task times for each of the 86 runs performed by the 18 test subjects and one run by the test director. For timing purposes, each run was divided into 16 tasks with easily identified end points. Since each task differed from and was largely independent of the others, the times have been grouped by task for maximum visibility of the varying characteristics of each.

The runs were performed in the order listed by each subject. Subscripts for configuration A indicate the three runs by each subject; no physical changes were made. Only thirteen subjects used configurations B and C, and three or less used D, E and F, because of time constraints. Average times were calculated only for configurations A, B and C, and are summarized in Table C-1. Task times for each subject are given in Tables C-2 (Installation) and C-3 (Removal).

One run by the test director, using configuration B, was timed to evaluate task times achievable after extensive practice (Table C-4). Prior to this run, he had about 27 hours of CAM 1400 operating experience, including 50 runs of this simulation, and in addition had observed more than one hundred runs by test subjects and visitors.

TABLE C-1
AVERAGE TIME BY TASK
(Minutes:Seconds)

TASK	CONFIGURATION			
	A ₁	A ₂	A ₃	B C
INSTALLATION				
1. Grapple Module	1:08	1:17	0:58	0:42 1:08
2. Insert Module	10:09	6:55	7:01	6:23 9:18
3. Pick Up Tool	1:42	1:07	0:45	0:27 3:43
4. Lock Pin 1	4:11	3:11	2:43	1:49 2:23
5. Lock Pin 2	3:19	2:30	2:29	1:05 1:33
6. Lock Pin 3	2:40	2:35	2:41	2:29 2:56
7. Lock Pin 4	2:43	2:25	2:25	0:57 1:47
8. Stow Tool	0:47	0:34	0:21	0:27 3:53
REMOVAL				
9. Pick Up Tool	0:51	0:35	0:37	0:25 2:07
10. Release Pin 1	3:04	2:56	3:00	1:34 2:14
11. Release Pin 2	2:56	2:51	2:36	0:31 1:43
12. Release Pin 3	3:07	3:28	3:08	0:59 1:25
13. Release Pin 4	2:47	2:54	2:39	0:33 1:07
14. Stow Tool	0:30	0:26	0:20	0:22 2:31
15. Grapple Module	1:09	1:03	0:51	0:36 1:48
16. Extract Module	2:09	0:38	1:26	0:48 1:33

TABLE C-2
INSTALLATION
(Times in Minutes:Seconds)

C-3

1. Grapple Module

CONFIG SUBJECT	A ₁	A ₂	A ₃	B	C	D	E	F
A	1:12	0:26	1:03	0:48	2:08			
B	1:25	2:17	1:30					
C	0:45	0:24	0:32	0:21	0:54			
D	0:30	1:50	0:55	0:21	1:07	1:54	0:20	1:05
E	1:06	0:45	0:23					0:08
F	0:35	1:52	0:46	0:20	0:50			
I	0:23	0:45	0:43	0:15	0:33	1:20		0:33
J	2:05	1:32	1:02	1:07	1:17			
K	1:14	0:43	1:37					
L	1:01	0:18	0:27	0:30	0:35			
M	1:00	0:30	0:48	0:18	0:40			
N	2:00	--	0:15	1:10	1:50			
O	0:42	1:42	1:40					
P	1:05	0:52	0:50	1:07	1:18			
Q	3:00	0:26	1:38	0:32	0:54			
R	0:53	1:05	0:38	0:51	1:26			
S	0:59	4:50	1:50					
T	0:30	1:40	0:45	1:24	1:15			
Avg.	1:08	1:17	0:58	0:42	1:08			

2. Insert Module

CONFIG SUBJECT	A ₁	A ₂	A ₃	B	C	D	E	F
A	5:03	40:54	5:03	1:27	3:39			
B	2:19	5:03	0:08					
C	22:35	8:51	7:19	6:07	9:09			
D	16:07	3:26	1:23	2:07	12:41	6:16	5:32	3:13
E	7:44	2:52	11:51					3:02
F	10:43	6:38	5:23	1:33	23:26			
I	4:47	3:37	4:55	4:03	3:30	8:26		2:03
J	13:45	9:16	5:23	13:58	3:17			
K	17:26	7:20	9:28					
L	24:42	6:14	4:37	11:56	3:00			
M	3:24	5:24	3:47	3:57	19:45			
N	2:45	0:40	11:02	13:15	12:30			
O	6:41	6:02	3:23					
P	9:10	7:40	2:22	3:46	10:37			
Q	5:08	3:33	39:52	10:43	7:01			
R	3:50	1:17	2:26	1:44	8:04			
S	12:06	3:32	4:27					
T	10:22	2:05	3:29	8:21	4:17			
Avg.	10:09	6:55	7:01	6:23	9:18			

INSTALLATION (cont)

C-4

3. Pick Up Tool

CONFIG SUBJECT	A ₁	A ₂	A ₃	B	C	D	E	F
A	1:05	0:40	0:26	0:25	3:01			
B	1:07	1:00	0:22					
C	0:55	0:55	0:24	0:52	2:01			
D	0:59	0:27	0:47	0:25	2:52	4:20	0:36	0:20
E	1:05	0:50	0:41					0:27
F	2:12	1:15	0:40	0:43	2:49			
I	0:42	0:35	0:31	0:25	1:29	1:14		0:26
J	2:08	1:20	0:40	0:50	2:27			
K	1:55	0:39	0:40					
L	1:17	0:35	0:29	0:28	4:49			
M	0:51	0:21	0:25	0:31	5:35			
N	0:52	0:55	0:32	0:30	8:52			
O	1:15	0:51	0:27					
P	1:15	1:02	0:36	0:20	2:48			
Q	0:52	0:56	1:00	0:35	3:08			
R	0:41	0:54	0:26	0:55	3:43			
S	10:30	5:53	3:33					
T	0:57	0:55	0:53	1:07	4:48			
Avg.	1:42	1:07	0:45	0:27	3:43			

4. Lock Pin 1

CONFIG SUBJECT	A ₁	A ₂	A ₃	B	C	D	E	F
A	2:14	2:42	1:40	1:40	2:00			
B	5:19	5:50	4:12					
C	3:45	2:20	1:37	1:50	1:11			
D	1:50	2:05	2:05	2:03	3:15	5:20	0:34	0:47
E	2:05	2:03	2:50					0:58
F	3:30	3:58	2:21	1:12	2:33			
I	3:23	1:59	1:55	1:15	1:18	1:48		0:44
J	2:58	2:29	2:57	2:55	1:39			
K	3:55	4:10	2:43					
L	1:55	4:08	3:07	2:32	3:02			
M	4:05	2:00	2:34	0:35	1:50			
N	3:28	1:55	1:58	2:05	2:38			
O	2:37	3:02	2:05					
P	2:50	3:22	3:04	1:12	2:12			
Q	10:18	2:12	3:30	2:28	2:22			
R	2:24	3:27	3:40	1:43	2:53			
S	10:35	6:15	3:55					
T	8:01	3:20	2:49	2:10	4:10			
Avg.	4:11	3:11	2:43	1:49	2:23			

INSTALLATION (cont)

C-5

5. Lock Pin 2

CONFIG SUBJECT	A ₁	A ₂	A ₃	B	C	D	E	F
A	3:31	1:40	1:36	0:33	1:54			
B	6:20	3:22	3:43					
C	2:30	2:10	1:48	1:05	1:50			
D	2:34	2:02	1:33	0:34	0:53	1:55	0:55	0:20
E	3:35	2:15	2:15					0:25
F	3:30	1:41	1:50	0:27	1:12			
I	1:30	1:35	1:34	0:20	0:50	5:12		0:55
J	5:39	2:41	2:13	0:48	1:35			
K	2:00	2:14	7:50					
L	3:28	3:30	3:17	1:24	1:22			
M	1:55	2:45	1:46	0:32	0:40			
N	4:45	3:02	2:56	0:55	1:13			
O	2:15	2:30	1:51					
P	3:04	1:59	2:00	0:57	1:12			
Q	1:14	2:08	1:35	0:28	3:37			
R	2:27	2:38	2:05	1:07	1:39			
S	6:30	4:08	2:15					
T	2:40	2:46	2:27	4:48	2:10			
Avg.	3:19	2:30	2:29	1:05	1:33			

6. Lock Pin 3

CONFIG SUBJECT	A ₁	A ₂	A ₃	B	C	D	E	F
A	1:55	1:33	1:46	2:37	6:40			
B	4:00	5:03	3:05					
C	3:20	1:50	1:45	2:21	0:31			
D	1:10	1:45	1:39	0:44	2:37	2:25	0:44	1:18
E	2:37	5:23	3:10					0:50
F	2:30	1:47	1:50	0:45	1:25			
I	1:45	1:49	1:22	1:12	1:20	1:20		1:53
J	3:15	2:18	4:25	2:05	3:57			
K	2:55	1:57	4:12					
L	3:07	2:50	3:08	5:25	3:27			
M	2:05	2:15	2:12	2:25	2:12			
N	3:30	1:56	2:37	2:30	2:30			
O	2:45	2:31	3:07					
P	2:23	3:20	2:57	2:23	3:25			
Q	1:43	1:52	2:15	0:39	2:06			
R	3:22	2:29	2:00	5:02	1:10			
S	4:17	3:32	4:35					
T	1:15	2:25	2:05	4:05	6:50			
Avg.	2:40	2:35	2:41	2:29	2:56			

INSTALLATION (cont)

C-6

7. Lock Pin 4

CONFIG SUBJECT	A ₁	A ₂	A ₃	B	C	D	E	F
A	3:03	1:40	1:31	0:25	1:43			
B	3:00	5:15	4:32					
C	2:06	1:58	2:37	0:29	0:39			
D	2:33	1:10	2:18	0:14	1:28	1:00	0:45	0:09
E	2:13	1:39	3:17					1:45
F	2:35	1:24	1:45	0:39	1:35			
I	1:08	1:13	1:34	0:17	0:30	2:10		0:24
J	2:35	1:55	2:20	2:07	3:43			
K	1:15	2:57	2:58					
L	2:10	1:30	2:27	1:15	1:45			
M	0:55	2:16	1:52	1:12	2:01			
N	2:22	3:47	3:02	1:18	0:57			
O	2:42	1:57	2:17					
P	3:17	2:10	1:37	1:45	3:23			
Q	4:50	2:26	2:20	1:25	2:12			
R	2:53	2:12	2:08	0:18	0:43			
S	5:13	4:25	2:18					
T	4:10	3:34	2:32	0:58	2:35			
Avg.	2:43	2:25	2:25	0:57	1:47			

8. Stow Tool

CONFIG SUBJECT	A ₁	A ₂	A ₃	B	C	D	E	F
A	0:29	0:15	0:14	0:18	2:01			
B	0:38	0:24	0:42					
C	0:34	0:32	0:27	0:17	1:23			
D	0:23	0:17	0:12	0:14	2:15	2:17	0:19	0:13
E	0:30	0:28	0:23					0:15
F	1:01	0:13	0:10	0:25	2:45			
I	--	0:09	0:09	0:22	1:10	1:49		0:22
J	0:53	0:25	0:21	1:12	6:25			
K	0:35	0:37	0:20					
L	0:20	0:23	0:21	0:25	4:55			
M	0:20	0:15	0:16	0:27	4:02			
N	0:30	0:17	--	0:27	7:38			
O	0:23	0:14	0:18					
P	0:41	0:25	0:19	0:20	3:20			
Q	0:23	0:26	0:18	0:35	6:45			
R	0:27	0:31	0:17	0:30	2:32			
S	4:35	4:00	0:55					
T	0:35	0:20	0:20	0:18	5:15			
Avg.	0:47	0:34	0:21	0:27	3:53			

TABLE C-3
REMOVAL
(Times in Minutes:Seconds)

C-7

9. Pick Up Tool

CONFIG SUBJECT	A ₁	A ₂	A ₃	B	C	D	E	F
A	0:44	0:25	0:18	0:14	2:23			
B	1:09	0:50	0:18					
C	0:20	0:23	0:19	0:12	0:18			
D	0:28	0:17	0:15	0:08	0:45	3:38	0:09	0:08
E	0:38	0:21	0:32					0:12
F	0:43	0:35	0:22	0:49	0:35			
I	--	0:26	0:23	0:09	0:20	0:18		0:07
J	1:49	0:30	0:40	1:05	2:10			
K	0:27	0:56	0:56					
L	0:32	0:26	0:12	0:08	1:45			
M	0:50	0:12	0:06	0:06	2:46			
N	0:34	0:13	0:35	1:00	1:00			
O	0:12	0:08	0:18					
P	0:22	0:20	0:34	0:02	0:18			
Q	0:45	0:51	0:36	0:24	9:55			
R	0:35	0:35	0:21	0:15	1:40			
S	3:20	2:30	3:40					
T	1:00	0:30	0:50	0:59	3:35			
Avg.	0:51	0:35	0:37	0:25	2:07			

10. Release Pin 1

CONFIG SUBJECT	A ₁	A ₂	A ₃	B	C	D	E	F
A	1:50	1:55	1:57	2:36	3:12			
B	4:45	3:39	3:05					
C	1:50	1:47	2:03	1:32	0:53			
D	1:49	2:06	2:17	0:37	2:18	1:22	0:26	0:15
E	4:12	2:06	2:33					0:23
F	1:32	3:30	1:49	1:19	1:20			
I	1:30	1:47	2:07	1:11	1:00	1:12		0:25
J	2:49	2:48	3:00	1:59	2:45			
K	4:03	2:37	5:16					
L	3:46	3:36	2:50	2:12	2:13			
M	2:05	3:03	2:04	0:35	1:19			
N	1:41	2:37	3:35	1:25	4:53			
O	3:18	3:28	4:42					
P	3:14	3:10	2:11	1:33	2:12			
Q	1:56	3:52	2:09	1:20	2:10			
R	4:45	2:47	3:44	0:52	1:13			
S	5:44	4:52	5:25					
T	4:25	2:59	3:13	3:17	3:28			
Avg.	3:04	2:56	3:00	1:34	2:14			

REMOVAL (cont)

C-8

11. Release Pin 2

CONFIG SUBJECT	A ₁	A ₂	A ₃	B	C	D	E	F
A	2:25	1:49	1:58	0:25	1:37			
B	2:51	5:00	3:22					
C	1:45	2:08	1:53	0:26	0:58			
D	1:43	4:27	1:19	0:50	1:02	1:30	0:24	0:27
E	4:15	2:15	2:55					0:10
F	1:57	2:16	1:57	0:16	0:45			
I	1:28	1:37	1:36	0:10	0:27	0:35		1:20
J	3:30	2:57	3:02	0:36	2:35			
K	5:05	2:34	4:04					
L	2:17	2:50	1:55	0:55	3:42			
M	1:40	2:33	1:55	0:19	1:45			
N	1:59	2:38	2:01	0:07	1:25			
O	2:05	2:23	2:45					
P	3:03	2:35	2:03	0:30	1:13			
Q	2:35	2:22	1:53	0:22	3:45			
R	2:42	4:00	4:45	0:51	2:02			
S	6:31	4:27	4:35					
T	4:55	2:33	2:42	0:50	0:59			
Avg.	2:56	2:51	2:36	0:31	1:43			

12. Release Pin 3

CONFIG SUBJECT	A ₁	A ₂	A ₃	B	C	D	E	F
A	2:00	2:03	1:51	0:57	1:08			
B	7:40	4:24	2:57					
C	2:20	1:32	2:13	0:19	0:39			
D	2:30	1:48	3:27	0:29	0:25	1:40	0:19	0:10
E	5:15	4:18	3:30					0:15
F	1:03	2:29	2:16	0:56	0:50			
I	2:17	1:57	2:29	0:20	0:51	1:07		0:39
J	3:32	2:28	3:57	0:45	1:35			
K	2:10	6:41	9:14					
L	4:03	2:58	3:23	2:35	1:30			
M	1:52	2:11	1:45	0:27	1:48			
N	2:14	6:45	2:10	0:36	0:46			
O	1:57	3:01	2:11					
P	2:50	3:05	2:27	0:53	1:37			
Q	2:28	2:25	2:37	3:04	2:22			
R	3:08	5:02	3:45	0:25	1:43			
S	4:00	5:31	2:50					
T	3:55	3:38	2:41	1:06	3:13			
Avg.	3:07	3:28	3:08	0:59	1:25			

REMOVAL (cont)

C-9

13. Release Pin 4

CONFIG SUBJECT	A ₁	A ₂	A ₃	B	C	D	E	F
A	1:45	1:53	2:00	0:21	1:12			
B	6:48	3:23	5:52					
C	2:37	2:20	3:02	0:13	0:37			
D	1:48	1:58	2:34	0:12	0:40	0:32	0:07	0:10
E	2:05	2:46	2:58					0:26
F	2:05	1:57	1:26	0:27	0:40			
I	1:40	1:38	1:39	0:11	0:21	0:20		0:11
J	2:22	2:01	2:53	0:29	0:47			
K	2:15	4:32	1:30					
L	2:20	3:33	3:03	1:35	1:35			
M	1:18	1:59	1:46	0:27	1:30			
N	2:05	3:04	1:59	0:21	1:37			
O	2:16	2:23	2:24					
P	3:10	2:45	2:12	0:54	1:05			
Q	2:11	3:20	2:17	0:15	1:23			
R	3:17	4:41	2:58	0:17	1:32			
S	5:00	4:26	4:05					
T	5:10	3:35	3:11	1:24	1:30			
Avg.	2:47	2:54	2:39	0:33	1:07			

14. Stow Tool

CONFIG SUBJECT	A ₁	A ₂	A ₃	B	C	D	E	F
A	0:28	0:14	0:17	0:17	2:30			
B	0:39	0:40	0:31					
C	0:26	0:21	0:17	0:12	0:50			
D	0:14	0:09	0:09	0:19	0:55	1:28	0:08	0:08
E	0:23	0:18	0:19					0:15
F	0:15	0:17	0:12	0:18	1:45			
I	0:17	0:11	0:14	0:14	0:46	0:50		0:16
J	0:43	0:22	0:20	0:58	3:13			
K	0:20	0:25	0:23					
L	0:22	0:22	0:17	0:27	2:50			
M	0:20	0:16	0:13	0:18	5:22			
N	0:24	0:15	0:16	0:21	3:12			
O	0:29	0:08	0:15					
P	0:24	0:20	0:18	0:17	2:30			
Q	0:27	0:22	0:22	0:15	1:37			
R	0:20	0:23	0:14	0:15	1:54			
S	2:00	2:17	0:48					
T	0:30	0:23	0:26	0:39	5:15			
Avg.	0:30	0:26	0:20	0:22	2:31			

REMOVAL (cont)

C-10

15. Grapple Module

CONFIG SUBJECT	A ₁	A ₂	A ₃	B	C	D	E	F
A	0:58	0:41	0:43	0:52	1:39			
B	1:48	1:20	1:23					
C	1:07	0:29	0:19	0:08	1:24			
D	0:58	0:36	0:29	0:42	1:07	2:00	0:30	0:23
E	0:32	0:28	0:28					0:14
F	1:10	0:51	0:44	0:40	2:10			
I	0:33	0:32	0:17	0:16	0:55	1:28		0:40
J	2:12	1:01	0:56	0:59	2:29			
K	1:02	1:15	0:57					
L	0:49	1:20	1:00	0:34	1:28			
M	0:25	0:48	0:31	0:29	1:16			
N	1:06	0:36	0:42	0:25	1:59			
O	0:43	0:39	1:05					
P	1:52	0:40	0:31	0:28	2:35			
Q	0:29	0:55	0:48	0:40	1:54			
R	1:23	1:17	0:33	0:49	0:58			
S	1:43	3:07	1:57					
T	1:45	2:12	1:21	0:52	3:27			
Avg.	1:09	1:03	0:51	0:36	1:48			

16. Extract Module

CONFIG SUBJECT	A ₁	A ₂	A ₃	B	C	D	E	F
A	0:11	0:13	1:04	0:23	1:21			
B	3:30	0:44	0:26					
C	4:50	0:11	1:50	0:09	5:39			
D	0:39	0:24	1:15	0:08	5:53	0:25	0:17	0:31
E	0:37	0:14	0:18					0:19
F	0:12	2:20	1:39	0:10	0:23			
I	0:17	0:14	0:45	0:49	0:26	3:32		0:18
J	3:13	0:15	1:30	4:49	0:31			
K	6:32	0:10	3:35					
L	4:11	0:12	1:20	1:50	0:12			
M	1:05	0:40	1:05	0:42	3:34			
N	0:59	0:52	0:07	0:04	0:13			
O	4:52	2:00	2:47					
P	0:12	0:07	1:14	0:36	0:50			
Q	5:51	0:07	4:03	0:08	0:14			
R	1:08	0:30	0:40	0:16	0:19			
S	0:08	1:38	1:25					
T	0:18	0:25	0:48	0:18	0:31			
Avg.	2:09	0:38	1:26	0:48	1:33			

TABLE C-4

HIGH-SPEED REFERENCE RUN

(Times in Minutes:Seconds)

INSTALLATION

Grapple Module	0:20
Insert Module	1:36
Pick Up Tool	0:18
Lock Pin 1	0:19
Lock Pin 2	0:09
Lock Pin 3	0:15
Lock Pin 4	0:11
Stow Tool	0:11

REMOVAL

Pick Up Tool	0:17
Release Pin 1	0:13
Release Pin 2	0:09
Release Pin 3	0:13
Release Pin 4	0:10
Stow Tool	0:10
Grapple Module	0:12
Extract Module	0:08

TEST SUBJECT QUESTIONNAIRE FOR SIMULATION #2

	Yes	No
1. Were the test objectives clear and precise?	___	___
2. Were the procedures for doing the simulation clear and precise?	___	___
3. What improvements do you suggest?		
4. Did the switching functions on the hand controller seem simple and straightforward?	___	___
5. Would you delete or add any functions to the hand controller?	___	___
6. Was the hand controller at the right height for ease of handling and movement?	___	___
7. Did the arm rest help you?	___	___
8. Were the feedback forces on the hand controller:		
Too low		
Just a bit too low	___	
Just right	___	
Just a bit too high	___	
Too high	___	
9. How important do you feel this aspect of force feedback is to operator success:		
Very important	___	
Average importance	___	
Unimportant	___	
Don't know	___	
10. Did you find yourself getting tired?	___	___
11. When did you first notice it?		
12. What do you think contributed most to your feeling tired?		

- | | Yes | No |
|--|-----|----|
| 13. What parts of your anatomy seemed to get tired first? | | |
| 14. Was the operator seat comfortable? | — | — |
| 15. Where would you improve on it? | | |
| 16. What suggestion do you have for improving the control and seating arrangement? | | |
| 17. Was the terminal device (grippers) easy to work with? | — | — |
| Can you suggest any improvements? | — | — |
| 18. Would more color coding facilitate their use? | — | — |
| 19. What improvements do you suggest? | | |
| 20. Were the TV controls conveniently located? | — | — |
| 21. Were the controls identified clearly as to their functions? | — | — |
| 22. Where would you locate the TV panel and controls? | | |
| 23. Can you suggest any improvements to the TV panel and controls? | — | — |
| If so, what | | |

- | | Yes | No |
|---|-----|-----|
| 24. Was the lighting level adequate for you? | ___ | ___ |
| 25. Do you think more contrast in the TV picture would help you? | ___ | ___ |
| 26. Which TV picture did you use most during adapter installation? | | |
| 27. Which TV picture did you use most during adapter removal? | | |
| 28. Did the TV cameras appear to be located in the best position to cover the different phases of the simulation? | ___ | ___ |
| 29. Do you have any suggestions for improving the TV aspects of the simulation. If yes, what improvements. | ___ | ___ |
| 30. Do you think marking (color coding) the screw drive adapter helped you? | ___ | ___ |
| 31. Would you recommend the use of more color coding. | ___ | ___ |

We would like to estimate how difficult this task seemed to you. The following is designed toward that goal.

32. Your estimate of the adapter installation is what percentage as difficult as driving your car at 60 mph on the LA freeway under the following condition.

Light flow of traffic	___%
Medium flow of traffic	___%
Heavy flow of traffic	___%

33. How difficult % wise do you estimate that the adapter installation is to parallel parking of your car between two vehicles ____%.

34. How difficult % wise do you estimate that the adapter installation is to backing your car out of a tight parking space in a busy parking lot. _____%.

35. Repeat the same for adapter removal.

Three conditions: _____%
 _____%
 _____%

36. Did the environment in which the simulation was conducted distract in any way?

Yes	No
_____	_____

Example: Too noisy, poor lighting,
 too many people around, etc.

What suggestions do you have on improving or making the task easier from the operator's point of view?